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Tennessee Valley Authority
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Div. of Energy Demonstrations and Technology

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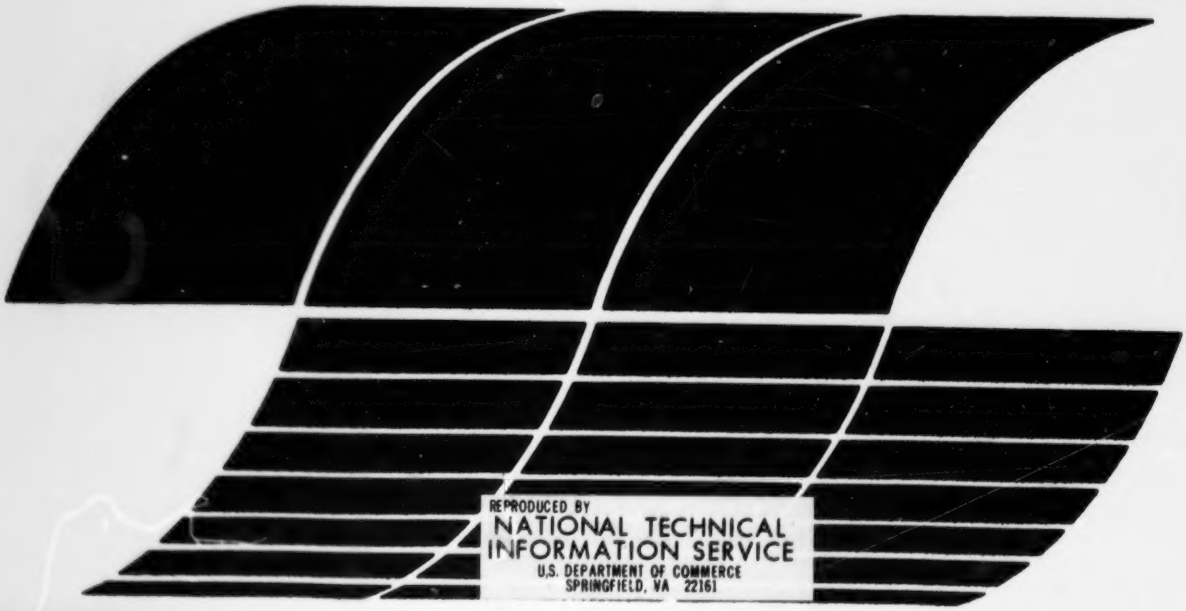
Interagency Energy/Environment R&D Program Report



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ABSTRACT

The comparative economics of utility ash disposal by five conceptual design variations of ponding and landfill were evaluated for a 500-MW power plant producing 5 million tons of ash over the life-of-project. For a basic pond disposal without water reuse, the total capital investment from hopper collection through one-mile sluicing and pond disposal is $52/kW (1982$). Comparable total system investment using trucking to a landfill is $30/kW. All disposal site construction costs were fully capitalized in both cases and this convention affects the comparison of annual revenue requirements. First-year annual revenue requirements for the ponding system are 1.85 mills/kWh (1984$), while those for the landfill system are lower at 1.66 mills/kWh. On the other hand, levelized annual revenue requirements are 2.26 mills/kWh and 2.42 mills/kWh respectively. Disposal site costs are the major element in all types of disposal and constituted the major difference in cost between pond and landfill disposal. Reuse of sluicing water and additional provisions for the disposal of self-hardening (high calcium oxide) ash added relatively little to costs.

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ECONOMICS OF ASH DISPOSAL AT COAL-FIRED POWER PLANTS

EXECUTIVE SUMMARY

INTRODUCTION

The use of coal in steam-electric power plants produces a sizable quantity of ash that presents an increasingly complex disposal problem. Coal cleaning and ash utilization tend to reduce the quantity of ash to be disposed of but other factors continue to increase the amount that must be discarded in an environmentally acceptable manner. Such factors include the steadily increasing amount of steam coal burned, the growing reliance on higher ash coals, and the increasing efficiency required in ash collection. In 1978 the electric utility industry burned almost 500 million tons of coal, generating almost 70 million tons of ash.

Conventional ash disposal has been mostly by sluicing to nearby ponds without reuse of the water. This practice has become increasingly unacceptable and expensive because of the large land requirements, the unavailability of suitable sites, environmental effects, higher land cost, and disposal regulations. As a result, dry or moist ash transportation and landfill disposal are becoming more common. In a number of cases ponds are used as dewatering and holding sites, followed by conveyance to a landfill.

This study examines the economics of five combinations of these disposal practices. The evaluations are based on technical and economic premises chosen for use in EPA-TVA studies. The results are arranged in modular form to facilitate cost comparisons. In addition, the estimated economics are compared with actual costs of ash disposal at TVA coal-fired power plants.

Five base case disposal processes are evaluated:

Base case 1: Direct sluicing of nonhardening (low calcium oxide) fly ash and bottom ash to separate ponds one mile from the power plant without water reuse.

Base case 2: The same as base case 1 with water return, treatment, and reuse.

Base case 3: Temporary ponding of nonhardening fly ash and bottom ash in 5-year-capacity ponds one-fourth mile from the power plant, followed by removal, dewatering, and truck transportation to a single landfill three-fourths of a mile from the ponds.

Base case 4: Disposal of nonhardening ash in separate landfills one mile from the power plant with dry collection of fly ash, dewatering of bottom ash, and truck transportation.

Base case 5: The same as base case 4 with self-hardening fly ash and provisions to prevent its hardening before disposal.

BACKGROUND

Most large utility boilers are fired with finely pulverized coal which is pneumatically injected into the boiler along with a portion of the combustion air. The coal burns at temperatures approaching 3,000°F while suspended in the highly turbulent combustion gases. Most of the ash solidifies in suspension as fine particles, a portion of which is carried out of the furnace in the flue gas as fly ash. The rest falls to the bottom of the furnace as bottom ash. In the most prevalent type of utility boiler, a so-called dry-bottom boiler, about 80% of the total ash is fly ash and 20% is bottom ash. A small portion of the fly ash settles in the boiler economizer and air heater but the majority remains suspended in the gas and must be collected downstream of the air heater. In dry-bottom boilers bottom ash falls through one or more throats in the bottom of the furnace as solid particles. The ash falls into water-cooled bottom ash hoppers with sloping sides and crushers at the ash outlet.

Fly ash is a gritty powder composed of aluminum and iron silicates and oxides along with numerous minor and trace components. Most of the particles are in the size range of 0.1 to 0.01 mm although some range upward to over 1 mm in size and downward to submicrometer sizes. Fly ash has a bulk density of 35 to about 100 lb/ft^3, depending on the degree of compaction. In many engineering properties it can be compared to a silty clay. In chemical composition it is a pozzolan, requiring only calcium oxide and water to undergo reactions such as occur in the setting of a hydraulic cement. Some western coals, in fact, contain sufficient free calcium oxide to produce a self-hardening fly ash that affects handling and disposal practices. Bottom ash is similar in gross composition but coarser and denser than fly ash. In texture and engineering properties it can be compared to a sandy gravel. It seldom has pozzolanic or self-hardening properties.

Utility ash production has a highly variable geographical distribution because of the regional variations in use of coal for electricity generation. As shown in Figure S-1, the major portion of utility ash has been produced in the central tier of states. By 1985, however, increased use of coal by utilities in the West and Southwest is projected to shift this production westward.

Most of the ash utilized is used for construction fill and concrete additives. Utilization has expanded from 12% of the ash collected in 1966 to 24% in 1978. Because of the increase in ash production, however, the quantity of ash disposed of has also increased at about 6% per year during the same period.

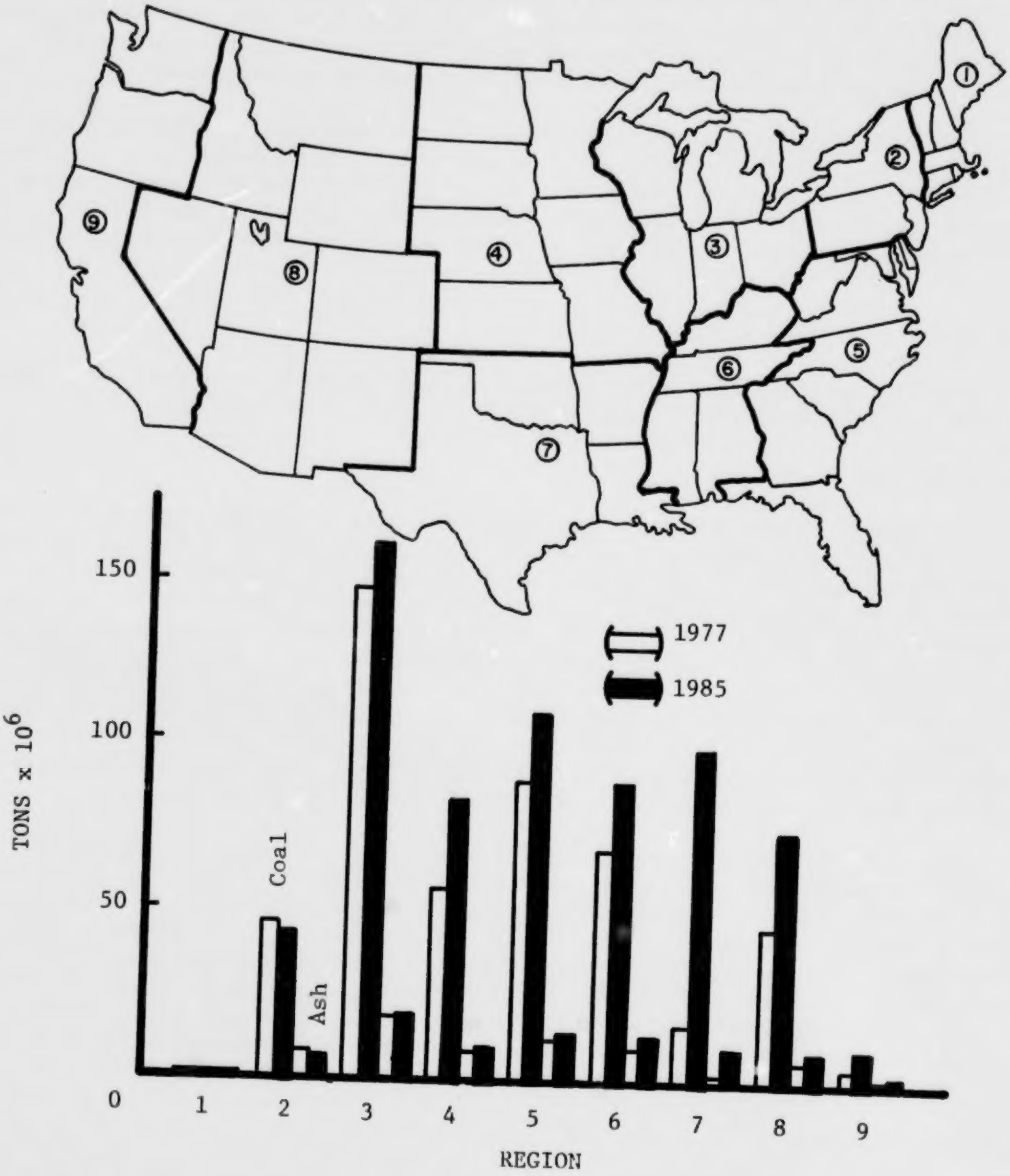

Figure S-1. Utility coal consumption and ash production by geographical region for 1977 and 1985. (Derived from Ref. 10)

The most common method of disposal, ponding of sluiced ash, is practiced by more than half of the U.S. utilities, especially by those east of the Mississippi River. In most cases, fly ash and bottom ash are sluiced separately or together to final disposal ponds. Many ponds take advantage of the natural topography and few have liners. In some cases, the ash is removed and landfilled to extend pond life. Some utilities use dry handling and landfilling for fly ash and temporary or permanent ponding for bottom ash. In lieu of temporary ponds, bottom ash may be dewatered mechanically.

Landfills are often chosen because of a shortage of nearby land for construction of ponds or of water for sluicing. They range from structured constructions to use of convenient depressions or excavations. Landfill management ranges from ash dumping with incidental spreading and compaction to well organized control of critical moisture levels and vibratory compaction.

PREMISES

The ash disposal evaluations included in this study are based on premises established in 1979-1980 for use in EPA-TVA economic evaluations.

Design Premises

The power plant basis is a new north-central, 500-MW, pulverized-coal-fired, dry-bottom power unit with a full-load operating schedule of 5,500 hr/yr over a 30-year life. The heat rate is 9,500 Btu/kWh. Two coals are evaluated, an eastern bituminous coal with a heating value of 11,700 Btu/lb containing 15.1% ash as fired and a western coal with a heating value of 9,700 Btu/lb containing 9.7% ash as fired. The eastern coal ash is assumed to be nonhardening when wet. The western coal is assumed to contain sufficient reactive calcium oxide to be self-hardening. For both coals 80% of the ash is emitted as fly ash and the remainder is bottom ash. The fly ash removal, mostly by an electrostatic precipitator (ESP), meets the emission level of the 1979 new source performance standards (NSPS), i.e., 0.03 lb/MBtu.

The ash disposal systems include all ash collection, handling, and disposal requirements, including bottom ash and fly ash hoppers. Ash hoppers are included in both capital investment and annual revenue requirements because the operation of the hoppers is a part of the overall disposal operations. Disposal sites include area for topsoil storage and operational facilities. Square earthen-diked clay-lined ponds constructed of onsite material and square area-type landfills with a clay base are used. Provisions for runoff control and reclamation are included. All disposal sites are sized for the 30-year life of the power unit.

Economic Premises

The evaluations are based on a 1981-1983 construction period and a 1984 startup. 1982 costs are used for capital investment and 1984 costs are used for annual revenue requirements.

Capital investment comprises direct investment, indirect investment, contingency, and other capital investment. Direct investment consists of the installed cost of equipment and a 4% allowance for services, utilities, and miscellaneous items. Indirect investment is factored based on direct investment.

The annual revenue requirements consist of direct and indirect costs comprising operating and maintenance costs and capital charges. The operating and maintenance costs are first-year costs and the capital charges are levelized over the life of the project. Direct costs for labor, utilities, maintenance, and analyses reflect the operating schedules within the plant. Indirect costs consist of a plant and administrative overhead cost of 60% of conversion costs less utilities and a levelized annual capital charge of 14.7% of total capital investment. No byproduct marketing credit is assumed. Levelized annual revenue requirements are the sum of levelized operating and maintenance costs and levelized capital charges.

SYSTEMS ESTIMATED

Base Case 1 - Direct Ponding of Nonhardening Ash Without Water Reuse

Ash is pneumatically collected from the economizer, air-heater, and ESP hoppers by twin hydraulic exhauster systems sized to operate 50% of the time. The hoppers have a 12-hour storage capacity. The economizer ash hoppers are uninsulated and are thermally isolated from the hot flue gas by a throat and chute. The air-heater hoppers are insulated and the ESP hoppers are heat traced and insulated. Two hydraulic exhausters discharge the air-ash-water mixtures to an air separator. The ash-water slurry at 7.7% solids flows by gravity from the elevated air separator through a 1-mile-long, 12-inch ID, schedule 80, carbon steel pipeline to the pond. A spare slurry pipeline is provided. Operation of the fly ash collecting system is nominally automatic but an operator oversees it on a 24 hr/day basis.

Bottom ash is collected in a double-vee bottom ash hopper with a 12-hour capacity. The upper section is lined with 9-inch-thick monolithic refractory and the bottom slopes are protected by a 6-inch-thick lining. Water overflows the seal trough on a continuous basis to wet the refractory lining. Each vee section has two double-roll grinders with a 2-inch roll spacing. The ash is sluiced through the grinders into one of two centrifugal slurry pumps (one pump is a spare). The 7.7% solids ash slurry is pumped through a 1-mile-long, 8-inch ID, basalt-lined pipeline to the bottom ash pond. A spare slurry pipeline of schedule 80 carbon steel is provided. Each pipeline has an agitator near its midpoint for reslurrying the ash-water mixture. The system is designed to operate about 2 hours each 8-hour shift.

The fly ash and bottom ash ponds are situated side by side at the disposal site. The overflow water, if above pH 9, is neutralized with sulfuric acid from an automatic pH control unit and the effluent water is sampled by an automatic sampler before discharge to the river.

Base Case 2 - Direct Ponding of Nonhardening Ash With Water Reuse

Base case 2 is identical to base case 1, except for the return and reuse of pond overflow water. The water is pumped from the disposal site through a pipeline to a surge tank at the power plant from which it is used for fly ash and bottom ash collection and conveyance. A lime-soda softener at the disposal site controls gypsum hardness in the returned water to minimize scaling.

Base Case 3 - Holding Ponds and Landfill for Nonhardening Ash

In base case 3, the fly ash and bottom ash collection systems are identical to those of base case 1. The conveyance systems are similar to those of base case 1 but the distance to the ponds is one-fourth mile instead of one mile. For these conditions, the hydraulic exhausters and air separator in base case 3 are situated at a lower elevation and require somewhat lower pressure in the supply water. A jet pump is used in place of a centrifugal pump for bottom ash conveyance.

The fly ash and bottom ash ponds of base case 3 are similar to those of base case 1, but they are sized for a 5-year capacity. Ash from both ponds is removed and hauled in 20-yd^3-capacity trucks to a common (fly ash plus bottom ash) landfill with a 25-year capacity.

Bottom ash is removed from the pond with track-type end loaders. Fly ash is pumped from the pond by a floating dredge to an adjoining drainage basin where it drains to 75% solids. The water returns to the fly ash pond. The drained fly ash is removed with front-end loaders. Dump trucks with a 20-yd^3 capacity are used to transport the ash to the common landfill. Trucks and landfill equipment operate 16 hrs/day.

Base Case 4 - Direct Landfilling of Nonhardening Ash

In base case 4 the fly ash is collected dry, moistened, and trucked to a landfill. Bottom ash is dewatered mechanically and trucked to a separate landfill. ESP ash and economizer-air heater ash are collected in a separate vacuum system and stored dry in a separate silo. A common vacuum source in the form of lobe-type mechanical exhausters is used. The ash is separated from the conveying air in centrifugal collectors and a bag filter. With the separate collecting systems, dry ESP ash is available for utilization, uncontaminated by economizer and air heater ash, which is coarser and may contain more carbon, making it less suitable for some uses. At the outlet of each ash storage silo, a high-capacity moisturizer, consisting of a screw conveyor with water sprays, increases the moisture content of the ash to 10% water for dust control and delivers it to 20-yd^3-capacity dump trucks.

Bottom ash is sluiced from the bottom ash hoppers, as in base case 1, and pumped one-eighth mile in a basalt-lined slurry pipeline to dewatering bins. Two dewatering bins alternate in operation. Water is recirculated to the bottom ash hopper and small streams supply the fly ash moisturizers. Drained bottom ash from the dewatering bins is hauled in 20-yd^3-capacity dump trucks to the bottom ash landfill.

The fly ash and bottom ash landfills are constructed and operated similarly to the common landfill in base case 3. At the fly ash landfill, water is added to obtain an optimum moisture level of 17% for vibratory compaction. The bottom ash is assumed to have an optimum moisture level of 10%, the moisture level at which it is removed from the dewatering bins.

Base Case 5 - Direct Landfilling of Self-Hardening Ash

Base case 5 duplicates base case 4 except in ash quantity and the self-hardening nature of the fly ash. Because of its self-hardening property, the fly ash is hauled dry in covered trucks to the fly ash landfill. Due to differences in ash content and heating value, the coal for base case 5 contains only 77% of the ash tonnage in the other base cases. This difference is reflected in equipment sizes.

Trucks for hauling dry fly ash to the landfill have covered 20-yd^3-capacity beds and onboard provisions for dust control when dumping. Each truck has a skirted tailgate, so that when the bed is raised for dumping, ash falls within the skirted confines. Water nozzles, supplied by an onboard water tank and pump, are mounted within the skirted section and spray the ash for dust control during unloading. Separate tank trucks add additional water for ash compaction. Bottom ash from the dewatering bins is transported to the landfill in a 7-yd^3-dump truck.

RESULTS

In addition to overall capital investment and annual revenue requirements, modular costs are developed by functional area.

Direct Capital Investment

Equipment costs are summarized in Table S-1. These uninstalled costs do not include slurry pipelines, which are covered in the piping category, or ponds, which are costed separately. Relative to the quantity of ash handled, the bottom ash equipment is more than twice as expensive as the fly ash equipment. The increase in equipment costs from base case 1 to case 2 is due entirely to return water facilities. Base case 3 has slightly lower process equipment costs because smaller pumps are used for the shorter pumping distance. However, in base case 3 mobile equipment comprises about one-half of the total equipment costs.

Process equipment costs in base case 4 are almost four times those of base case 1 because of the more elaborate collection and storage of dry fly ash and the mechanical dewatering of bottom ash. Mobile equipment is less costly in base case 4 than in base case 3, which includes ash retrieval from the ponds. Base case 5 has higher mobile equipment costs than base case 4 because of the need for separate fly ash trucks with covered beds and moisturizing equipment.

The construction costs for ponds and landfills are shown in Table S-2. They represent separate full-life ponds and separate full-life landfills for the same ash tonnages. The costs represent only the disposal site, without land, mobile equipment, or other conveying provisions, or allowance for services, utilities, and miscellaneous needs.

TABLE S-1. COST OF DELIVERED EQUIPMENT

	1982 k$				
Base case:	1	2	3	4	5
Fly Ash					
Hoppers	421	421	421	421	356
Process equipment	341	484	348	1,154	934
Vehicles	0	0	899	545	598
Subtotal fly ash	762	905	1,668	2,120	1,888
Bottom Ash					
Hoppers	352	352	352	352	310
Process equipment	147	183	132	674	604
Vehicles	0	0	309	137	136
Subtotal bottom ash	499	535	793	1,163	1,050
Total Ash					
Hoppers	773	773	773	773	666
Process equipment	488	667	480	1,828	1,538
Vehicles	0	0	1,208	682	734
Total	1,261	1,440	2,461	3,283	2,938

TABLE S-2. TYPICAL DISTRIBUTION OF POND AND LANDFILL CONSTRUCTION COSTS

	Separate ponds, base case 1		Separate landfills, base case 4	
	1982 k$	%	1982 k$	%
Land clearance	343	3	128	5
Excavation, soil storage	3,975	37	439	18
Dike construction	2,309	22	-	-
Liner installation	1,222	11.5	556	23
Catchment ditch, basin	-	-	295	12
Ditches, roads, fence, etc.	475	4.5	241	10
Reclamation	2,312	22	774	32
Total	10,636	100	2,433	100
Pond/landfill volume,[a] Myd^3	6.93		4.21	

[a] Based on 171,600 tons/yr of ash.

Both the total costs and the profiles of cost differ markedly for the two cases. In landfills the compacted ash volume is about 60% of that of settled ash in ponds. Also, it is practical to construct landfills, at least on level terrain, at a considerably greater height than ponds. For both ponds and landfills, the most costly requirement is the movement and placement of earth. For ponds this constitutes about two-thirds of the total cost. The earthmoving costs for landfills are much less because dikes are not required and excavation is minimal.

Pond and landfill construction costs are summarized in Table S-3 for the five base cases. The 5-year ponds of base case 3 accommodate only 17% of the ash tonnage of the 30-year ponds but their cost is 30% of the 30-year ponds, reflecting an economy of size. The difference in landfill costs between base cases 4 and 5 is due principally to ash tonnage.

TABLE S-3. POND AND LANDFILL

CONSTRUCTION COSTS

1982 k$

	Ponds	Landfills	Total
Base case 1	10,636	-	10,636
Base case 2	10,636	-	10,636
Base case 3	3,142	1,863	5,005
Base case 4	-	2,433	2,433
Base case 5	-	2,037	2,037

Total Capital Investment

Total capital investment is summarized in Table S-4. The difference between base cases 1 and 2 is for water reuse facilities. In base case 3, the capital investment is lower because the pond-landfill costs, which predominate in direct investment, are less than half those of the prior cases. They more than offset the mobile equipment costs for ash retrieval from the ponds. Since base case 4 has landfills without ponds, its capital investment is lower. Base case 5 has a still lower capital investment because of its smaller ash tonnage.

In cost per ton of ash handled the capital investments are lowest for direct landfill (base case 4) and highest for direct ponding (base cases 1 and 2). Also, relative to material handled, the bottom ash investment is 1.5 to 2.2 times that for fly ash. The higher values represent mechanical dewatering of bottom ash in base cases 4 and 5.

Table S-5 shows the distribution of capital investment among the major functional areas. In all cases the disposal site constitutes the largest element, but it is a much lower percentage of total costs in landfill cases.

TABLE S-4. SUMMARY OF CAPITAL INVESTMENTS

1982 k$

	Total capital investment, k$	Unit capital investment	
		$/kW	$/annual ton ash
Base Case 1			
Fly ash	18,880	37.7	138
Bottom ash	6,980	14.0	203
Total	25,860	51.7	151
Base Case 2			
Fly ash	19,800	39.6	144
Bottom ash	7,220	14.4	210
Total	27,020	54.0	157
Base Case 3			
Fly ash	11,630	23.3	85
Bottom ash	4,500	9.0	131
Total	16,130	32.3	94
Base Case 4			
Fly ash	9,650	19.3	70
Bottom ash	5,100	10.2	149
Total	14,750	29.5	86
Base Case 5			
Fly ash	8,190	16.4	78
Bottom ash	4,460	8.9	170
Total	12,650	25.3	96

TABLE S-5. MAJOR COST ELEMENTS IN CAPITAL INVESTMENTS

	Percentage of total capital investment				
Base case:	1	2	3	4	5
Cost Element					
Ash collection	8	8	13	16	15
Ash transportation	7	7	10	18	18
Disposal site	43	41	35	20	21
Water treatment and recycle	-	3	1	3	3
Proportioned costs[a]	34	34	34	38	38
Land	8	7	7	5	5

a. Indirect investment, contingency, other capital investment, working capital.

Annual Revenue Requirements

Annual revenue requirements are shown in Table S-6. Base case 5 has the lowest annual revenue requirements because of the lowest quantity of ash. In terms of cost per ton of ash it is the highest. Base case 4, with mechanical dewatering of bottom ash and trucking of fly ash and bottom ash to separate landfills, has lower annual revenue requirements than base case 1 with conventional pond disposal. The reuse of pond water in base case 2 adds 0.13 mill/kWh or about 7% to the costs. Base case 3 with its pond-landfill combination has annual revenue requirements only 3% higher than base case 1 with ponds, but 14% higher than base case 4 with landfills.

Major elements of annual revenue requirements are shown in Table S-7. In all cases, the capital charges are dominant; ranging from 47% of the total annual revenue requirements for a landfill process to 75% for a pond process. Maintenance, at 9% to 12%, is important in all cases, and labor is high in the cases with mobile equipment. As a result, overheads are also high in the mobile equipment cases.

TABLE S-6. SUMMARY OF ANNUAL REVENUE REQUIREMENTS

1984 k$

	Total annual revenue requirements, k$	Unit annual revenue requirements	
		Mills/kWh	$/dry ton ash
Base Case 1			
Fly ash	3,570	1.30	26.0
Bottom ash	1,510	0.55	44.1
Total	5,080	1.85	29.6
Base Case 2			
Fly ash	3,840	1.40	28.0
Bottom ash	1,600	0.58	46.5
Total	5,440	1.98	31.7
Base Case 3			
Fly ash	3,850	1.40	28.0
Bottom ash	1,400	0.51	40.8
Total	5,250	1.91	30.6
Base Case 4			
Fly ash	2,950	1.08	21.5
Bottom ash	1,600	0.58	46.6
Total	4,550	1.66	26.5
Base Case 5			
Fly ash	2,740	1.00	26.1
Bottom ash	1,570	0.57	60.0
Total	4,310	1.57	32.8

TABLE S-7. MAJOR COST ELEMENTS IN ANNUAL REVENUE REQUIREMENTS

	Percentage of total annual revenue requirements				
Base case:	1	2	3	4	5
Labor	4	4	17	17	20
Process reagents	-	-	-	-	2
Utilities					
Electricity	1	2	1	1	-
Diesel fuel	-	-	4	3	3
Maintenance	10	10	9	12	11
Sampling and analysis	1	1	1	1	1
Dredging	-	-	4	-	-
Overheads	9	9	19	18	20
Capital charges	75	73	45	47	43

Modular Costs

Modular capital investments by process area are shown in Table S-8 and modular annual revenue requirements by process area are shown in Table S-9. In all cases, the capital investment for the disposal site is the largest cost, ranging from 36% for direct landfill to 71% for direct ponding. Similarly, in annual revenue requirements, the disposal site is the most costly process area, ranging from 37% for direct landfill to 60% for direct ponding. Ash collection costs show little variation due to method. Truck transportation costs are 50% to 60% higher than pipeline conveyance. Water treatment and recycle costs are lowest in base case 1 and highest in base case 2, which included return and reuse of the water.

To some extent, pond and landfill disposal sites have offsetting annual revenue requirements. The cost of operating the pond disposal site in base case 1 is 80% higher than the cost for operating the landfill site in base case 4. When the ash transportation costs are included, however, base case 1, with its high-cost pond and low-cost transportation, is only 28% more expensive than the low-cost landfill with its high-cost transportation. Differences in water treatment costs further narrow the gap so that the total annual revenue requirements of base case 1 are only 12% higher than those of base case 4.

TABLE S-8. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

	1982 k$				
	Collection	Transportation	Disposal site	Water treatment and recycle	Total
Base Case 1					
Fly ash	2,337	1,791	14,648	105	18,891
Bottom ash	1,524	1,765	3,662	28	6,979
Total	3,861	3,556	18,310	133	25,860
%	15	13	71	1	100
Base Case 2					
Fly ash	2,337	1,791	14,648	1,025	19,801
Bottom ash	1,524	1,765	3,662	270	7,221
Total	3,861	3,556	18,310	1,295	27,022
%	14	13	68	5	100
Base Case 3					
Fly ash	2,340	1,452	7,620	216	11,628
Bottom ash	1,481	1,095	1,868	57	4,501
Total	3,821	2,547	9,488	273	16,129
%	23	16	59	2	100
Base Case 4					
Fly ash	2,734	2,582	4,231	105	9,652
Bottom ash	1,524	1,824	1,064	689	5,101
Total	4,258	4,406	5,295	794	14,753
%	29	30	36	5	100
Base Case 5					
Fly ash	2,272	2,204	3,609	105	8,190
Bottom ash	1,304	1,610	903	638	4,455
Total	3,576	3,814	4,512	743	12,645
%	28	30	36	6	100

TABLE S-9. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

	1984 k$				
	Collection	Transportation	Disposal site	Water treatment and recycle	Total
Base Case 1					
Fly ash	681	385	2,451	54	3,571
Bottom ash	423	442	615	34	1,514
Total	1,105	827	3,065	88	5,085
%	22	16	60	2	100
Base Case 2					
Fly ash	681	380	2,451	330	3,842
Bottom ash	423	440	615	116	1,595
Total	1,105	821	3,065	446	5,437
%	20	15	57	8	100
Base Case 3					
Fly ash	680	1,219	1,837	112	3,848
Bottom ash	409	474	456	62	1,402
Total	1,089	1,692	2,294	174	5,250
%	21	32	44	3	100
Base Case 4					
Fly ash	751	798	1,348	57	2,954
Bottom ash	420	535	350	296	1,600
Total	1,171	1,333	1,698	354	4,555
%	26	29	37	8	100
Base Case 5					
Fly ash	647	747	1,285	57	2,736
Bottom ash	365	494	324	387	1,575
Total	1,012	1,241	1,609	444	4,311
%	24	29	37	10	100

Case Variations

Trucking distance, land cost, ash collection rate, and ash utilization were evaluated to determine their effects on the cost of ash disposal.

Increasing trucking distance (at an average highway speed of 30 mph) increases capital investment 20,000 \$/mile for base case 3, 14,000 \$/mile for base case 4, and 9,000 \$/mile for base case 5. For a distance of 50 miles, the increase in ash disposal capital investment is 6%, 5%, and 4%, respectively, compared with the 1-mile distance. The increase is a result of the additional trucks required and varies among the cases because of the different water contents (base case 3 versus base case 4) and ash quantities (base case 4 versus base case 5).

Annual revenue requirements are affected by the additional direct operating costs of the vehicles such as labor, fuel, and maintenance as well as additional capital charges and overheads. Annual revenue requirements increase at rates of 23,000 \$/mile for base case 3, 17,000 \$/mile for case 4, and 10,000 \$/mile for base case 5. The increase in first-year annual revenue requirements for ash disposal are 22%, 18%, and 12%, respectively, compared with the 1-mile distance. As in capital investment, these costs are affected by the different moisture contents and ash tonnages of the base cases.

Ash collection rates (representing different coal properties and power plant operating conditions) were evaluated for each base case process, at rates 24% above and 24% below the ash rate of base cases 1 through 4. The low rate is the same as that of base case 5. The results (Figure S-2) show slightly curved relationships between costs and ash rates but the relationships are defined more clearly by cost-to-rate exponents of the type: cost 1 = cost 2 (rate 1/rate 2)$^{\text{exp}}$. The exponents are:

Exponent for:	Base cases 1, 2	Base case 3	Base cases 4, 5
Capital investment	0.75	0.71	0.67
Annual revenue requirement	0.68	0.68	0.64

For both capital investment and annual revenue requirements, the lower exponents for base cases 4 and 5, using landfills, mean that landfills have slightly greater economy of scale than do the ponds in base cases 1 and 2.

Land costs of \$1,000, \$10,000, and \$15,000 per acre, as compared with the base case cost of \$5,000 were evaluated. The effects on overall costs are moderate. For example, increasing the cost of land from \$5,000 per acre to \$15,000 per acre increases base case 1 capital investment by 15% and annual revenue requirements by 11%.

The effects of utilizing 25% and 50% of the ash without changing the proportions of fly ash and bottom ash disposed of were evaluated. Utilized ash is assumed to be removed from the ponds in base cases 1 to 3 and from the fly ash silos and dewatering bins in base cases 4 and 5 at no cost to the utility. The main cost effects are in reduced trucking requirements and reduced disposal site requirements. The percentage changes in capital investment and annual revenue requirements are shown below.

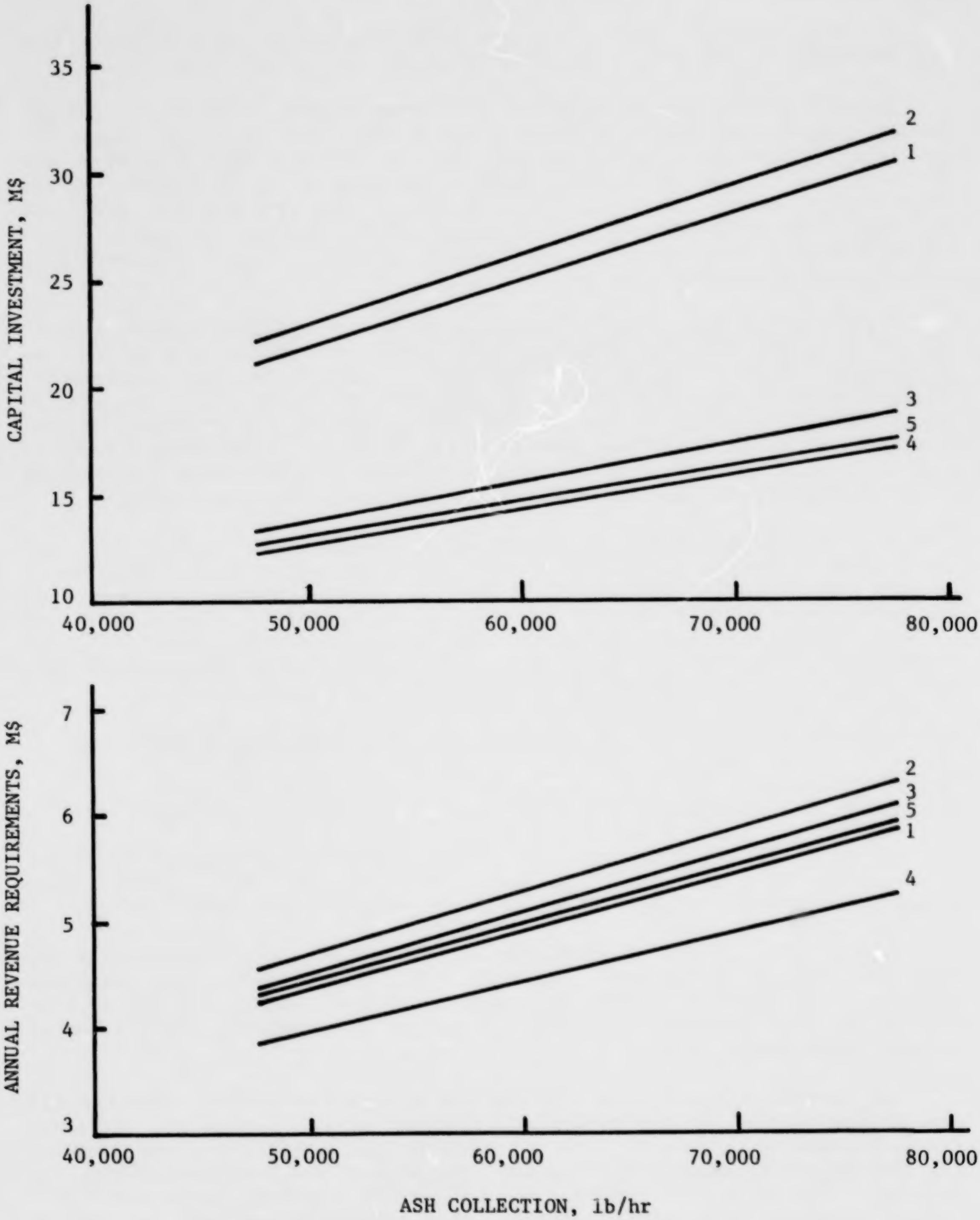

Figure S-2. Effect of ash collection rate on costs, base cases 1 through 5.

Percentage utilization		Capital investment percentage decrease	Annual revenue requirements percentage decrease
Base case 1:	25	14	12
	50	30	26
Base case 2:	25	14	11
	50	29	25
Base case 3:	25	10	9
	50	17	18
Base case 4:	25	9	9
	50	16	18
Base case 5:	25	11	10
	50	16	18

Utilization results in larger savings in base cases 1 and 2 than in base cases 3, 4, and 5. This difference is due to the much larger cost of ponds compared with landfills.

COMPARISON WITH TVA ASH DISPOSAL COSTS

Information on actual costs of TVA ash disposal was used in performing these evaluations. However, some data were not directly applicable because of different time frames, accounting practices, designs, and economic bases. It is possible, however, to compare certain aspects of the costs developed in this study with actual ash disposal costs at TVA coal-fired power plants. Eight TVA plants were selected for cost comparisons with the base case 1 conceptual design. The eight plants have dry-bottom pulverized-coal-fired furnaces burning bituminous coal. They were constructed in the period 1951 to 1973. The average station capacity is 1,600 MW and the average unit capacity is 260 MW. In 1978 the average yearly ash production was 563,000 tons per plant. (In comparison, base case 1 represents a 500-MW power unit producing 171,600 tons of ash per year.) The bottom ash is typically sluiced from the hoppers through clinker grinders and pumped through steel pipelines with centrifugal pumps. Fly ash is typically removed from the flue gas with ESP's or mechanical collectors and collected with vacuum systems using water exhausters. It is sluiced to the ponds through steel pipes, either separately or combined with the bottom ash. The water is not reused. The onsite ponds differ in size, configuration, and construction technique and are situated from a few hundred feet to over one mile from the power plants.

The most relevant comparison of base case 1 direct capital investment can be made with the installed costs of ash disposal equipment for two power units at two TVA plants constructed in 1963 and 1965. Indirect costs cannot be readily compared because of differences in accounting and financial practices. The base case 1 operating and maintenance costs can be compared with TVA operating and maintenance costs for all eight of the TVA plants. The TVA costs are also adjusted for size, pipeline length, and other factors as discussed below.

Equipment Cost Comparisons--

The costs of installed ash disposal equipment at the two TVA power plants used and the nature of the adjustments needed for comparison with base case 1 are shown in Table S-10. The TVA cost adjustments consist of: (1) an increase in the bottom ash hopper capacity from 8 to 12 hours, (2) an adjustment in the pipelines to a one-mile length, basalt lining, and spare provisions, (3) a size factor based on a cost-to-size exponent of 0.8, and (4) an inflation factor. The ESP hopper costs are excluded from the base case 1 costs because they are not differentiated in the TVA ESP costs. As can be seen in Table S-10, the comparable, generalized conceptual design costs are within 5% to 10% of actual adjusted TVA costs for similar systems.

Operating and Maintenance Cost Comparison--

The operating and maintenance costs (excluding ponds) for ash disposal from 1970 to 1978 at the eight TVA plants are shown in Figure S-3. Also shown is the base case 1 operating and maintenance cost from the projected 1984 costs developed in this study and the 1978 TVA average cost projected to 1984 using the cost indexes discussed in the premises.

The TVA costs comprise the operating labor and the maintenance labor and materials for removal of ash from the hoppers, sluicing to the ponds, pond maintenance, and treatment of the discharge water. Costs for electricity are not included. In 1978 the average TVA ash production rate per plant was 562,500 tons of ash, producing an average operating and maintenance cost of $1.95 per ton. Projected to 1984 using the premise indexes, the costs become $3.07 per ton.

The conceptualized base case 1 operating and maintenance costs, excluding electricity, are $766,800, or $4.47 per ton in 1984 dollars based on 171,600 tons per year of ash. Assessment of the systems involved results in an appropriate size correction factor of 0.79. Applying this correction, the base case 1 costs become $3.53 per ton in 1984 dollars.

Design differences other than plant size and ash tonnage lead to small or offsetting differences in operation and maintenance cost. For example, a reduction in length of slurry pipeline from 1 mile to 1/2 mile would lower pipeline maintenance by $0.10 per ton of ash but greater ash dilution in the TVA pipelines increases their size, and hence maintenance cost, by a similar amount.

At $3.53 per ton of ash, the base case 1 cost for operation and maintenance is 15% higher than the projected 1984 average TVA cost of $3.07 per ton of ash.

CONCLUSIONS

The most common current method of utility ash disposal, sluicing to a permanent pond with no water recycle, has a higher capital investment (52 $/kW) and annual revenue requirements (1.85 mills/kWh) than landfill disposal capital investment (30 $/kW) and annual revenue requirements (1.66 mills/kWh) for the same power unit conditions.

TABLE S-10. INSTALLED COST OF TWO TVA ASH DISPOSAL SYSTEMS

Equipment	Adjustments[a]	Plant A TVA cost, k$ (1963)	Plant A Adjusted cost, k$ (1982)	Plant B TVA cost, k$ (1965)	Plant B Adjusted cost, k$ (1982)	Base case 1 k$ (1982)
Bottom Ash						
Hopper assembly	8 to 12 hour capacity, unit size, inflation	290	932	324	699	
Disposal piping system	Extension to 1 mile, basalt lining, share of spare line, unit size, inflation	26	527	81	606	
Water supply system	Unit size, inflation	20	54	62	107	
Total, bottom ash			1,513		1,412	1,772
Fly Ash						
Handling system	Inclusion of hopper insulation, unit size, inflation	123	457	175	497	
Disposal piping system	Extension to 1 mile, share of spare line, unit size, inflation	104	773	324	771	
Water supply system	Unit size, inflation	79	214	250	430	
Total, fly ash			1,444		1,698	1,482[b]
Total		642	2,957	1,216	3,110	3,254

a. Unit size factor is 0.93 for plant A, 0.60 for plant B; inflation factor is 2.93 for plant A, 2.88 for plant B.
b. Excluding fly ash hoppers.

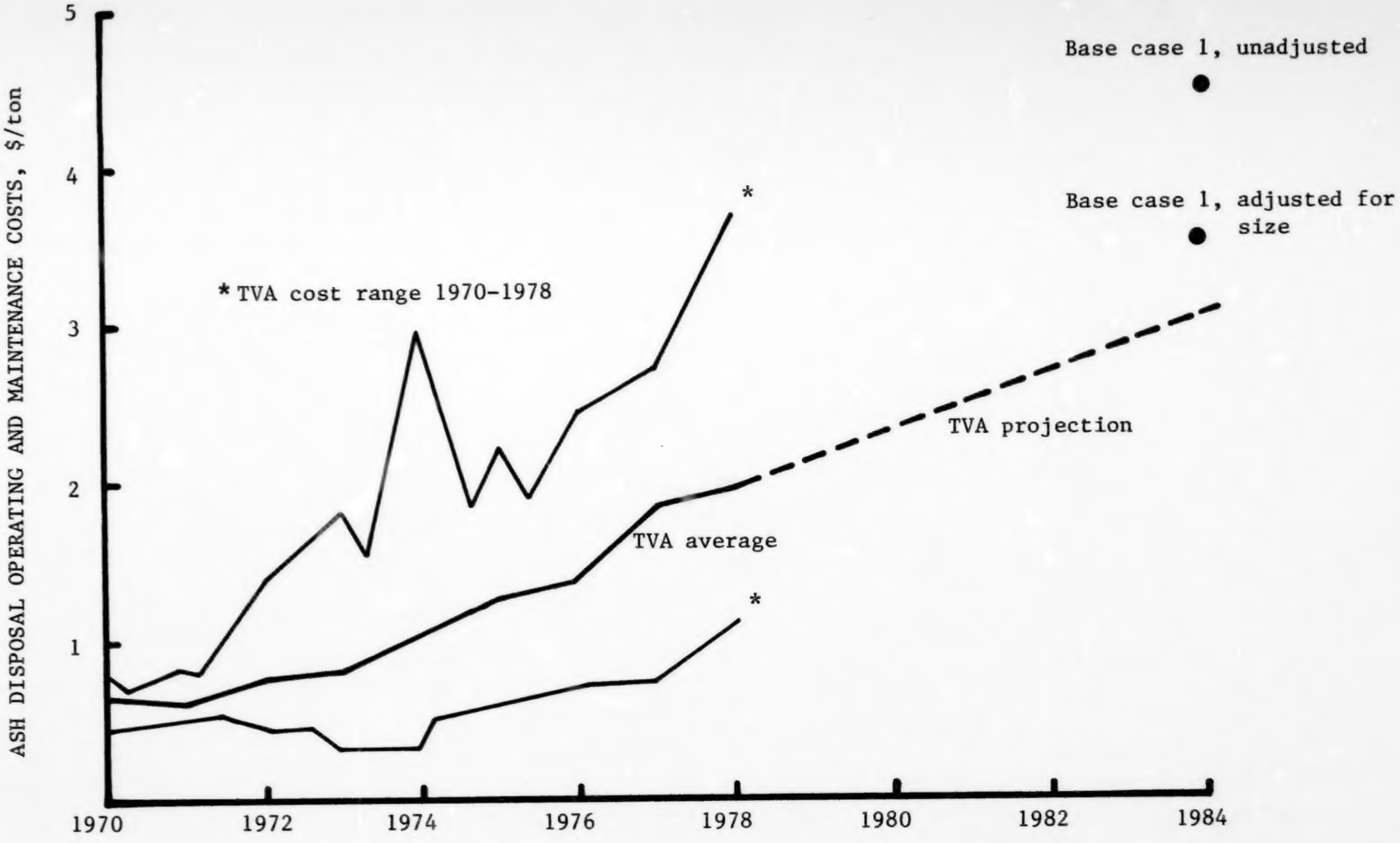

Figure S-3. TVA and base case 1 operating and maintenance ash disposal costs.

Temporary ponding followed by removal of the ash to a landfill has a capital investment (32 $/kW), similar to that for landfill, but higher annual revenue requirements (1.91 mills/kWh) than either direct ponding or landfill. There is no apparent economic advantage in using temporary ponds at new plants. Reuse of sluicing water, including treatment to prevent scaling, only slightly increases capital investment and annual revenue requirements.

The costs for disposal of a self-hardening ash are slightly higher in cost per ton of ash than disposal costs for nonhardening ash. The higher costs are due to the use of covered trucks with moisturizers and addition of all moisture for compaction at the landfill site instead of at the storage silos. The main cost differences are slightly higher truck costs and slightly higher bottom ash water treatment costs.

In all cases, disposal site costs are the largest cost element in both capital investment and annual revenue requirements. Pond cost constitutes two-thirds of the capital investment and landfill costs constitute about one-third of the capital investment in the respective processes. The capital investment contribution to annual revenue requirements as capital charges is the largest factor in total annual revenue requirements.

Trucking distance has little effect on capital investment and increases annual revenue requirements moderately because of increased operating costs and labor requirements. Moisture content has an important effect on trucking costs.

Ash utilization has a significant effect on costs, particularly for pond disposal processes. Fifty percent utilization reduces capital investment and annual revenue requirements about one-fourth for pond disposal and one-sixth for landfill disposal.

Although the design differs considerably between collection of ash for wet sluicing and for trucking the overall costs for ash collection systems do not differ greatly. The capital investment for truck transportation (including storage silos) is about one-third higher than the capital investment for sluicing. The annual revenue requirements for trucking are about twice as high as those for sluicing.

Base case 1 direct capital investment excluding ponds, and operating and maintenance costs excluding electricity, are in general agreement with selected equivalent TVA costs when the TVA costs are adjusted for unit size and cost-basis year.

ECONOMICS OF ASH DISPOSAL AT COAL-FIRED POWER PLANTS

INTRODUCTION

Ash disposal has been practiced at coal-fired power plants since their beginnings a century ago. The amount of ash for disposal has continued to grow as ash-producing factors have expanded. Such factors include the increasing use of steam coal, the increasing reliance on higher-ash coals, and the increasing frequency and efficiency in ash collection. For 30 years, coal use by electric utilities has increased at 5% to 6% per year, supported by capacity increases and, more recently, by a trend from use of natural gas and oil to use of coal for new power units. On the other hand, the disposal requirements for this increased ash production have been partially offset by the increasing quantities of ash utilization in cement production, road construction, and other uses.

Over the years, conventional ash disposal has been mostly to ponds, less frequently to landfills, and sometimes to combinations of the two. The land requirements have increased with ash production. At many locations, the availability of suitable disposal sites is becoming a problem that is complicated by the size of site needed, its distance from the power plant, its soil conditions and topography, the sensitivity of the surroundings, and land cost. Recently, Federal and State regulations for disposal have added new dimensions to the requirements for site preparation, management, and closure. The interaction of these factors has made decisions on ash disposal practices more complex. As a result, the economics of various ash disposal methods are becoming an increasingly important factor in decisions related to disposal methods.

The purpose of this study is to evaluate the economics of ash disposal practices for large coal-fired utility power plants representative of current and projected requirements. Disposal methods using ponds, landfills, and their combination, are chosen as base cases to depict both established practice in the industry and state-of-the-art practice that may be required at many new plants. Because of differences in both the amount and handling characteristics between ash from subbituminous and most bituminous coals, both types are included. The effects of variations in distance to the disposal site, in land cost, in type of ash transportation, and ash utilization are also included. Other solid and liquid power plant wastes are omitted from the study. Among these exclusions are mill rejects from coal pulverization, sludge and other products from flue gas desulfurization (FGD), water treatment sludges and brines, and miscellaneous washing or refuse streams.

The five base cases evaluated are (1) direct ponding without water reuse, (2) the same process with reuse of sluicing water, (3) temporary ponding followed by landfill, (4) landfill, and (5) landfill of a self-hardening (high-calcium) ash.

The design and economic premises follow the applicable premises used in related EPA-TVA studies of sludge disposal and FGD. The study is based on new installations. The cost and operation of various segments of a new system could be similar to those in a retrofit installation, but retrofit conversion is highly site specific and it is not included in the scope of this study.

In addition, the estimated costs developed in this study are compared with actual TVA costs in areas where costs are available and similarities in the methods permit. All TVA ash is disposed of by sluicing to ponds, hence the comparisons are limited to pond disposal.

BACKGROUND

Utility ash disposal practices in the coming years will depend on many interrelated factors. The total utility coal consumption will determine, in part, the quantity of ash produced. The geographical source areas will also in part determine the quantity of ash and, more importantly, the chemical and physical properties of the ash. These properties are important determinants in boiler design, which also affects the characteristics of the ash produced. Finally, patterns of ash utilization and environmental regulations governing disposal practices will affect ash collection, handling, and disposal methods. Many of these factors are in a state of change. Projections of coal use by utilities vary; traditional geographic patterns of coal production and utility coal use are changing; the effects of recent environmental legislation are not fully clear; and ash utilization is becoming a subject of increasing interest and complexity.

UTILITY COAL USE AND COAL CHARACTERISTICS

Numerous projections of coal use for electricity generation have been made in recent years, most of which have been widely published and more widely discussed (1). Though at variance in many aspects, these projections generally predict an increasing role for coal in electricity production, with consumption increasing to over 700 million tons by 1985. This is supported by the dominance of coal as the fuel for new fossil-fuel units (2) as well as an increasing dominance of fossil-fuel units over nuclear units in recent new construction (3). Continuing growth in utility coal use is projected for the rest of the century.

The quantity of ash produced by coal consumption rates of these magnitudes is enormous. In the early 1970's coal ash production ranked in the top ten of nonfuel mineral production tonnages, exceeding such materials as phosphate rock and salt in tonnage produced (4). By 1977 it ranked fourth, exceeded only by crushed stone, sand and gravel, and cement. In 1985, at the projected growth rates for these materials (5) and utility coal use, the tonnage of coal ash produced will be exceeded only by crushed stone and sand and gravel. The projected 1985 coal consumption by utilities of 700 million tons could produce over 100 million tons, or over 2 billion cubic feet, of ash.

The geographic distribution and characteristics of U.S. coals are well documented (6,7). Historically, bituminous coals from the Appalachian region and the Central basins supplied almost all U.S. needs. In the 1970's, the use of western coal and lignite from the Northern Great Plains and Rocky Mountain regions and lignite from the Gulf Coast region greatly increased. Continued increase in the use of western coal by utilities is seen in Department of Energy surveys, both by the increasing number of western power plants (8) and the increasing use of western coals east of the Mississippi River (9). The effect of these trends on regional coal consumption and ash production is shown in Figure 1. The Department of Energy analyses, however, note a downward trend from previous studies in both projected western power-plant construction and in coal shipments to eastern areas. These projections antedate the final promulgation of the 1979 revised NSPS (11) which restrict the use of low-sulfur coal in lieu of coal cleaning or flue gas desulfurization. More recent projections, however, support the trends toward greatly increased use of western coals (12).

Although intraregional and even intrabed variations often exceed regional variations, several generalizations of interregional differences in coal characteristics can be made. Almost all eastern utility coals, including those of the Central basins, are agglomerating, or coking, relatively high-sulfur bituminous coals that produce ash relatively low in calcium and high in iron, compared with western coals. Most western utility coals are nonagglomerating, or noncoking, relatively low-sulfur subbituminous coals or lignite that produce ash relatively low in iron and high in calcium, compared with eastern coals. Other regional characteristics, such as chloride and sodium contents also exist. Radian Corp. (13) and Gibbs & Hill, Inc., (14) among others have summarized data on regional variations. These variations affect the characteristics of the ash produced not only directly but indirectly through their influence on boiler design.

UTILITY BOILER DESIGN

Several types and numerous variations of types of utility boilers exist. These are extensively described in the literature (15,16,17). A limited number of stoker-fired boilers are used. These are small and are not a major factor in considerations of ash utilization and disposal. Except for a limited number of cyclone furnace designs, large, modern coal-fired utility boilers burn pulverized coal. Buonicore and others (18) cite unpublished data showing that about 1% of utility coal is burned in stoker boilers, 14% in cyclone boilers, 72% in dry bottom pulverized coal-fired boilers, and 14% in wet bottom pulverized coal-fired boilers.

In pulverized coal-fired boilers the coal is ground to a fine powder (typically 70% to pass 200 mesh, the consistency of talcum powder) and injected into the furnace through burners as a suspension in a portion of the combustion air. The remaining combustion air is injected around the burner periphery and at other locations to control combustion conditions. Numerous burner and furnace designs exist, depending in large part on the characteristics of the coal and the ash it produces. Most constructed in the last 10 years or under construction are horizontally or tangentially fired; the burners are aligned to inject the coal-air mixture horizontally into the furnace or from the furnace corners tangential to an imaginary circle at the center of the furnace. Figure 2 shows a generalized horizontally fired boiler.

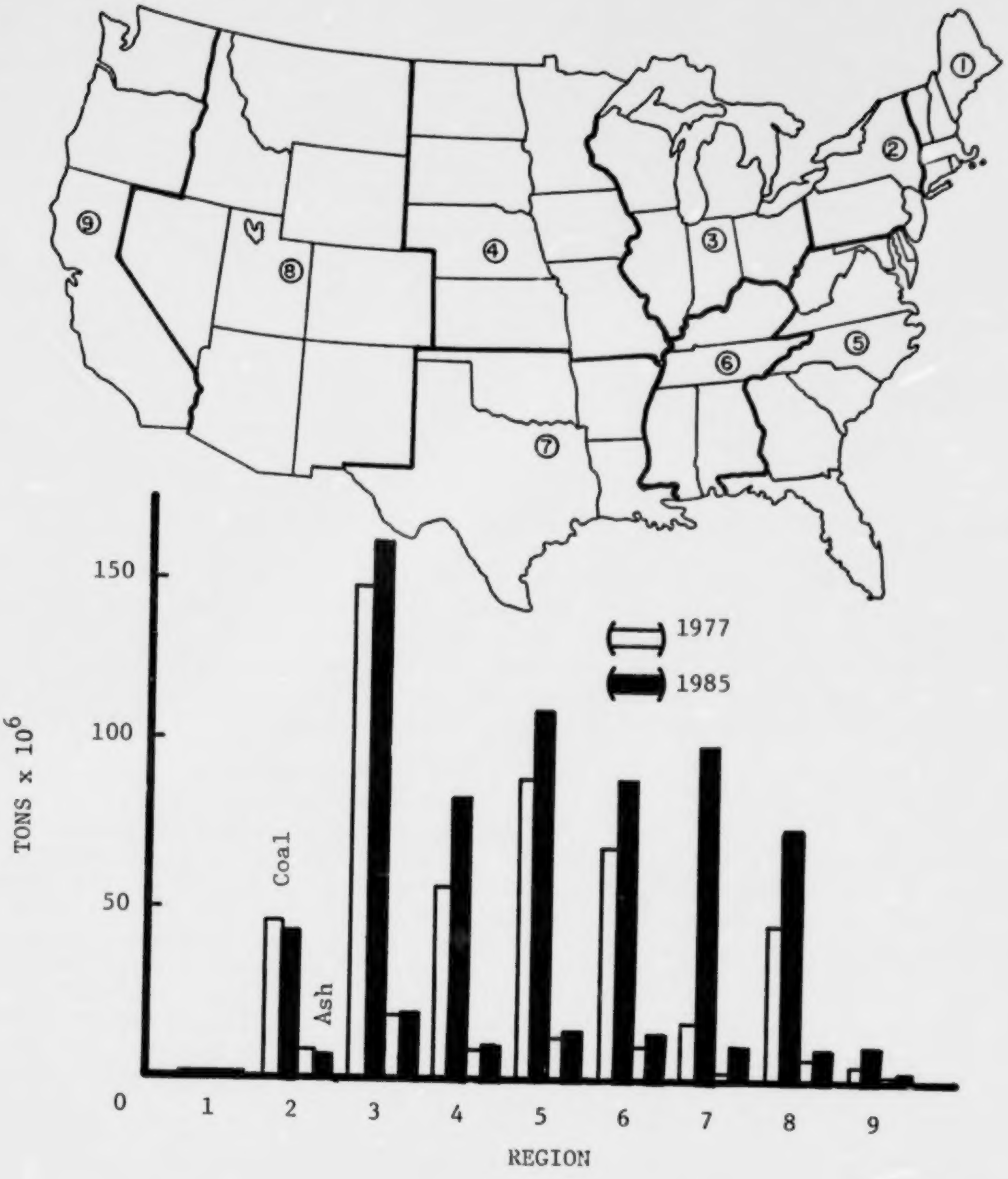

Figure 1. Utility coal consumption and ash production by geographical region for 1977 and 1985. (Derived from Ref. 10)

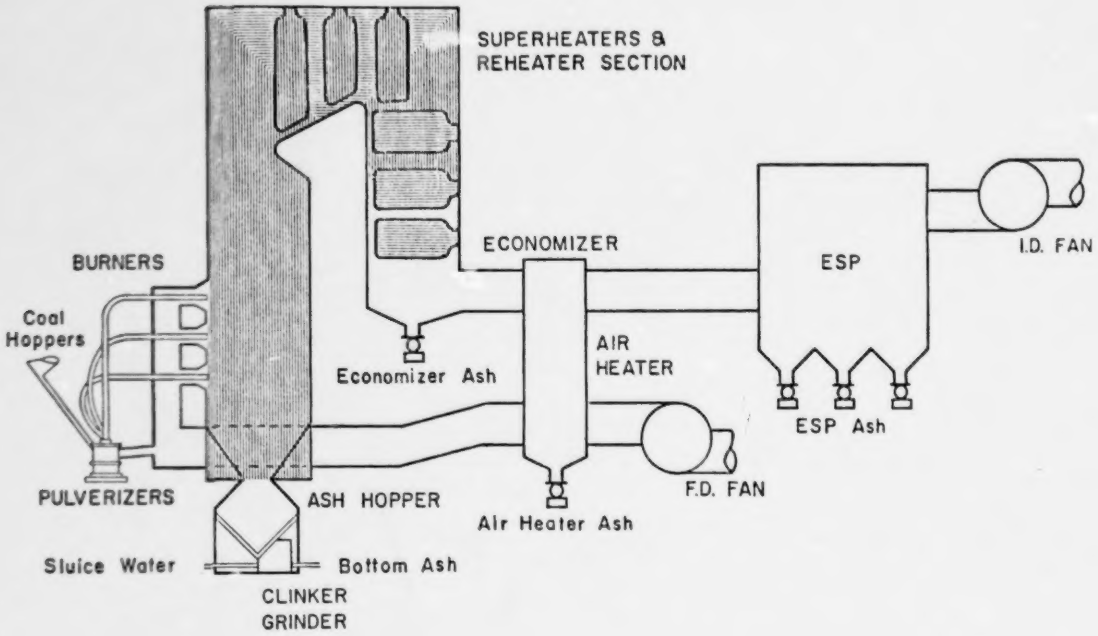

Figure 2. Generalized pulverized coal-fired utility boiler.

The furnace consists of a vertical chamber (sometimes with internal partitions) lined with water tube walls that constitute the steam generating area. The pulverized coal injected in the primary air burns in the confines of the furnace while mixing with the secondary air injected through the burners and tertiary air injected at other locations in the furnace.

The furnace may be designed so that the ash solidifies while suspended in the combustion gases before contacting the furnace walls. In this case part of the ash, usually about 20%, falls to the bottom as solid particles. Such designs are called dry bottom or dry ash boilers. If this is impractical because of the melting characteristics of the ash, the bottom of the furnace is designed to operate above the melting temperature of the ash so that ash impinging on the furnace surfaces drains to the bottom as slag. These are called wet bottom or slag tap boilers. In these furnaces about 50% to 65% of the ash in the coal is removed as slag. In either case the furnace is designed so that the ash remaining in the flue gas solidifies before leaving the furnace. Although dry bottom boilers predominate in numbers, the use of wet bottom designs is common. In a survey of 41 new boilers by Friedlander (2) 13 plants reported a wet bottom design.

Bottom ash and occasional chunks of slag, if the furnace is designed as a dry bottom unit, fall through a throat at the bottom into an ash hopper. Bottom slag, if it is a wet bottom design, drains down the walls through a throat into an ash hopper. Dry bottom ash hoppers usually have sloped, ceramic-lined bottoms that are continually washed with water to quench the ash. Wet bottom furnace ash hoppers are usually similar, water-filled hoppers. Both types are equipped with a clinker grinder. Clinker grinders, with single- or double-toothed rolls, reduce the quenched slag to a maximum size of about 2 inches, allowing it to be sluiced into the disposal system.

The flue gas, containing the fly ash, passes upward at about 50 to 70 ft/sec and leaves the furnace at about 2000°F. It then passes through banks of superheater and reheater tubes in which it is cooled to about 1000°F. Finally, it passes through the economizer, which heats the boiler feedwater, and the air heater, which heats the combustion air. The flue gas enters the air heater at about 700°F and leaves it at about 300°F, a temperature dictated by the necessity of keeping the flue gas above the sulfuric acid saturation temperature.

Slagging (accumulation of solids on the furnace walls) and fouling (similar accumulations on convection tubes) are unavoidable handicaps of coal-fired boilers. Soot blowers, situated at strategic locations in the furnace and convection sections, dislodge this material, some of which falls to the bottom of the furnace, contributing a slag component to the suspension-solidified dry bottom furnace ash.

Flow of air into and flue gas through the boiler is provided by forced draft (FD) fans that blow air into it and induced draft (ID) fans that draw flue gas from it. Most boilers are designed to operate at slight negative or positive pressures in the range of 0 to 2 in. H_2O. Many are balanced draft designs in which the top of the furnace operates at a slight (about -0.1 in. H_2O) negative pressure. The quantity of flue gas leaving the boiler is determined by the quantity of air needed for efficient combustion and the quantity of air that leaks in or is added as tempering air. The total quantity of air entering the furnace is usually about one-fifth greater than the stoichiometric combustion requirements. Air heater leakage can add an equal volume of dilution air.

Ash characteristics such as softening and fusion temperature, chemical composition and ratios of chemical constituents, and abrasiveness are important considerations in boiler design. Insofar as these relate to coal rank and geographic source, boiler design is related to the coal rank and source. Boilers designed for lower rank coals generally have more conservative heat release rates (Btu/ft^2 of radiant heated surface) and are larger in height and plan area. Flue gas velocity may be lower, resulting in a higher ratio of bottom ash to fly ash. To decrease fouling, the temperature of the flue gas leaving the furnace may also be lower.

A second modern design, the cyclone furnace, is in more limited use. It is particularly suited to low-rank, high-ash coal that has a low fusion temperature and is difficult to grind. Crushed coal (not pulverized) is blown into horizontal ceramic-lined, water-cooled combustion chambers that occupy the same positions as the burners of a pulverized coal boiler. Combustion air is injected to impart an extremely turbulent circular flow pattern so that the coal burns rapidly at a very high temperature. About four-fifths of the ash-forming components are trapped on the furnace walls and are tapped as slag. The fly ash loading is thus low but it is high in the more difficult to remove submicrometer size range (19). Cyclone furnaces have seen limited application in recent years, in part because of the high levels of nitrogen oxides emissions they produce. However, they continue to be selected for some new plants, particularly those burning lignite (2).

COAL MINERAL MATTER AND COAL ASH

The mineral content of coal consists of a small fraction of minerals incorporated into the growing plants, and a larger fraction of detrital and authigenic material dispersed through the coal during its accretion, diagenesis, and postdiagenic history. An additional quantity of mineral matter is incorporated during mining by the inclusion of surrounding rock, partings, and nodules. Numerous compendiums and summaries of coal mineral studies exist (20,21, for example). The major minerals normally consist of clays, calcium and iron carbonates, quartz, iron sulfides, and gypsum, with clays usually predominating. A number of minor elements (1.0% to 0.1%) consisting of metal sulfides, oxides, carbonates, and aluminosilicate minerals also occur. In addition, many trace elements (less than 1000 ppm) occur in coal. As they are in most organic-rich sedimentary rocks, many of these elements are abnormally concentrated, often by orders of magnitude, compared with normal crustal abundances. The occurrence of these elements in coal ash has been extensively studied and reported (22,23) because of their potential physiological effects.

Although the mineral matter in coal is widely studied, it is more commonly characterized by the ash, determined by controlled combustion tests or analysis of boiler ashes. Ash compositions and physical properties determined from laboratory tests may not exactly reflect the characteristics of an ash produced by the same coal in a boiler, nor will the ash produced in a particular boiler necessarily characterize ashes from the same coal in other boilers.

In a pulverized-coal-fired boiler the coal particles are about 100 micrometers in size. At this size the bulk homogeneity of the coal is lost and the particles range in composition from essentially pure coal to pure mineral matter. In the furnace the coal is pyrolyzed, forming char as the volatilized matter burns. The char may, depending on the coal, pass through a liquid stage, as it in turn is burned. This combustion process occurs in less than a second at temperatures of about 3000°F while the particles are suspended by the turbulence of the injected combustion air and burning gases. Some mineral matter in the coal particles forms molten particles. Other particles composed mainly or wholly of mineral matter are melted or softened. These particles continue to react, combine, and disintegrate until they solidify in the flue gas or impinge upon and stick to the furnace walls. Some ash components such as carbonates and sulfides, are decomposed and form gaseous oxides. Components such as the alkali metals and numerous trace elements are partially or wholly vaporized and condense as submicrometer particles or as surface coatings on existing particles as the gas cools, creating a fractionation of elements between the fly ash and bottom ash. The final physical and chemical characteristics of the ash depend on the original coal composition, the degree of pulverization, and the time-temperature-turbulence history of the particles. The final composition is a mixture of vitreous and crystalline oxides and silicates in which silicon, aluminum, iron, and sometimes magnesium and calcium are major components.

FLY ASH

Fly ash is composed of well-graded particles ranging in size from a small fraction of a micrometer to over 100 micrometers, a range encompassing the sizes of clay through fine sand. The geometric mean diameter is usually in the range of 10 to 20 micrometers, with 1% to 10% below 1 micrometer and about 90% below 100 micrometers (19). Southern Research Institute (24) reports similar data for pulverized coal ashes and describes measurement techniques. The morphology of fly ash particles has been widely described. Published scanning electron microscopy photomicrographs (25,26, for example) have made its appearance familiar. Most fly ash particles consist of vitreous, often translucent, spheres that are frequently hollow to some degree and may contain smaller spheres (27). Others consist of irregularly shaped particles, fragments of spheres, sintered agglomerates, and porous carbonaceous fragments. The term cenosphere has been variously applied to the hollow spheres as a generic term (26) and as a term for the fraction that floats in water. The major constituents, reported as oxides, are silicon, aluminum, and iron. Calcium, magnesium, and sodium seldom exceed 2% each in most ashes from eastern bituminous coals. In ashes from western coals and lignites, however, the calcium content usually exceeds that of iron and is usually in the 10% to 20% range. Magnesium and sodium contents are also usually higher in western coals. Carbon contents are highly variable, often less than 1% but ranging up to 20% (22) or higher (28). Carbon content is, of course, a function of perhaps transient combustion conditions rather than intrinsic properties.

A host of other elements occur in fly ash. These have been extensively studied (20,22,23, and 29 all provide extensive compilations). Many of the 25 to 40 elements abnormally concentrated in coal occur in the ash at levels sufficient to cause apprehensions as to the environmental effects of its disposal or use. Among these are radionuclides (30,31) and numerous physiologically active elements. Most of these elements, particularly antimony, selenium, arsenic, and lead are enriched in the fly ash fraction of the ash.

There is also a considerable variation of chemical composition with particle size, and in some cases between the surface and interior portions of the particles. This is true of both major and minor elements as a result of the original inhomogeneity of the coal particles and the thermal fractionation that occurs during combustion and subsequent cooling. Coles and others (32) in addition to the authors cited above provide a discussion with extensive references of these phenomena.

Although the compositions of coal ashes are almost always reported as the oxides or as elemental components, X-ray crystallographic and petrologic studies have reported a number of oxide, silicate, sulfate, and other minerals in fly ash. This mineral composition and its variation along with chemical composition and fractionation, is undoubtedly an important factor in the chemical and physical behavior of the ash.

In appearance fly ash is a gritty powder ranging from black through various earthy colors to light tan. In many engineering properties fly ash is often compared to a light silty soil. It differs in several, some advantageous, aspects, however. Chae and Snyder (33), Srinivasan and others (34), and Seals and others (35) have described specific engineering studies. GAI Consultants, Inc., (36) have summarized fly ash engineering properties, along with an extensive discussion of their measurement and application.

Fly ash grain size is well graded and generally falls in the size distribution range between silty clay and silty sand. Specific gravities of less than 2.0 to 3.0 have been reported (37) but those in the range of 2.1 to 2.6 are commonly reported, considerably lower than soils of similar particle size, which are in the 2.5 to 2.8 range. Aerated dry bulk densities of 35 to 65 lb/ft^3 (38) and compacted dry bulk densities of 75 to over 100 lb/ft^3 (33) have been reported. The dry bulk density of fly ash settled in ponds may be considerably less, however (39). Dry fly ash lacks cohesion although it develops a considerable apparent cohesion at certain moisture levels because of capillary attraction, a property of dubious value in engineering considerations of shear strength. Values for the angle of internal friction between 25° and 40° are cited by GAI Consultants (36), a range that spans those of common soils from clay (19°-28°) to gravels (about 38°). Generalizations of shear strength are complicated by cementitous reactions that may occur with time, particularly with high calcium fly ashes. Fly ash is also generally described as having no plasticity, a common soil property, as measured by Atterburg limits tests. The compressibility of fly ash, the tendency to decrease in volume under load, is similar to the compressibility of a cohesive soil such as silt. Permeabilities vary considerably. GAI Consultants (36) report a range of 10^{-7} to 10^{-4} cm/sec for compacted fly ashes, a range encompassing clay through porous silt. The degree of compaction has been shown to have an important effect on permeability (34), as have cementitious reactions.

Very little has been published on the dewatering characteristics of fly ash. GAI (36) cites a study in which capillary rise in fly ash could range from 6 to 32 feet. DiGioia and others (40) cite a study of an unidentified temporary ash pond with an impervious liner in which the capillary rise in fly ash was 7 feet. The ash had to be stacked and drained beside the pond before it could be trucked. The capillary zone was eliminated by an underdrain.

FLY ASH COLLECTION

Some fly ash settles out in low-velocity areas of the boiler such as the economizer and air heater. Economizer ash shares some characteristics with bottom ash. It is coarse compared with fly ash and sometimes contains appreciable unburned carbon. Economizer ash also has a tendency to sinter if it remains in contact with the hot flue gas. It is sometimes collected in water hoppers and sometimes in dry hoppers thermally isolated from the flue gas by a throat or chute. Its disposal may be either a part of the bottom ash sluicing system or the fly ash pneumatic system.

Fly ash can be removed from flue gas with mechanical collectors, wet scrubbers, electrostatic precipitators (ESP's), or fabric filters. To meet the current emission regulations very high removal efficiencies, usually above 99% and sometimes higher than 99.9%, are required. Mechanical collectors (41) cannot meet these requirements. They are used when partial cleaning is desirable in conjunction with other control devices. Wet scrubbers are in use at several utility power plants (42) and are planned for others (2). The primary disadvantages of scrubbers are the high energy requirements because of the large flue gas pressure drops necessary for high removal efficiencies and the large volumes of liquid that must be circulated. Wet scrubbers, many of novel design, continue to be an important factor in utility fly ash control, however (43).

ESP's have been widely used in industrial applications for many years and are well described in emission control literature (19,48). Particles are collected in an ESP by charging them by exposure to ions and passing them through an electrical field between two electrodes so that they migrate to and collect on one of the electrodes. In the most common electrical utility ESP, the ions are created by a corona discharge from a negatively charged wire or wirelike electrode between two platelike passive collection electrodes. As the flue gas passes through arrays of these electrodes the fly ash particles become charged and adhere to the collection electrode. Periodically the fly ash layer is removed, usually by rapping the electrode, and collected in inverted-pyramidal hoppers beneath the electrodes.

Removal efficiencies well in excess of 99% can be practically attained under many conditions. The specific collection area (SCA), expressed as collection electrode area per unit volume of flue gas ($ft^2/1000\ ft^3$) is largely determined by the fly ash resistivity. Uncommonly, a low resistivity can result in rapid particle charge decay and reentrainment. More characteristic of coal fly ash, high resistivity results in a low corona current flow and reduced collection efficiency and eventually in electrical breakdown of gases in the particle layer. In addition to fly ash composition, fly ash resistivity is determined by flue gas temperature and the presence of materials such as SO_3 and sodium in the flue gas. The most desirable ESP location is usually downstream from the air heater where the operating temperature and flue gas volume are lower, ducting is simplified, and heat losses minimized. These cold-side ESP's operate at about 300°F, near the temperature of maximum resistivity for fly ash. For collection of high-resistivity fly ashes a hot-side ESP situated between the economizer and air heater is sometimes more practical. Resistivity is also reduced by the presence of gaseous conditioners such as SO_3 for cold-side ESP's and sodium for hot-side ESP's, either present in the coal or introduced as an additive. Numerous other additives have been evaluated (49).

In general, high-sulfur Eastern U.S. coals produce ash more amenable to collection in ESP's and low-sulfur Western U.S. coals produce ash less easily collected. Cold-side ESP efficiencies in excess of 99% can often be attained at SCA's of 100 to 300 $ft^2/1000\ ft^3$ with fly ash from Eastern U.S. coal, while SCA's for Western U.S. coals under similar conditions would be over 500 $ft^2/1000\ ft^3$.

Fabric filters are a more recent adaptation to utility flue gas emission control, their development for this use paralleling the development of durable cloths that are practical at the temperatures involved. Bechtel (44) has discussed the early applications of fabric filters in utility fly ash collection. Utility interest has been summarized by Reigel and Bundy (45) and more recently by EPA symposium compilations (46). A typical fabric filter baghouse installation consists of arrays of fabric tubes, often about 1 foot in diameter and 30 to 40 feet long, attached at their open ends to a dividing tube sheet partition in the baghouse enclosure. Flue gas enters through the bottom open end of the commonly used low-ratio designs, with inside to outside flow, and passes through the bags into the bag compartment. Periodically the fly ash layer is dislodged by a reversed flow or a reversed pulsed flow of air, or by mechanical shaking, or both, and falls into a collection hopper.

Interest in fabric filters has been increased in recent years by several factors. Very high collection efficiencies needed to meet stringent emission regulations are sometimes achieved more easily and economically by fabric filtration. Fabric filters are insensitive to fly ash characteristics such as resistivity that affect the efficiency of ESP's. In addition, fabric filters are efficient collectors of the 0.1 to 1.0 micrometer particles that are physiologically important (47) and also cause opacity problems.

BOTTOM ASH

Compilations of data on bottom ash are less extensive than those on fly ash. Rose (28), Ray and Parker (29), and Moulton (50) have published physical and chemical data. Srinivasan and others (34), Digioia and others (40), and Magidzadeh and others (51) have discussed engineering properties. Bottom ash from dry bottom furnaces consists of dark, highly vesiculated, vitreous, angular to spherical fragments with a size distribution of about 0.1 to 40 mm. Texturally, the particles range from dense pieces of slag to porous, sintered agglomerates. Bottom ash has a major element composition similar to fly ash, mostly aluminum and iron silicates and oxides, but it is depleted in volatile elements relative to the original coal mineral composition. It is also usually less reactive than fly ash because of the larger, more vitreous nature of the particles (20). Loss on ignition (representing for the most part unburned carbonaceous material and sulfur) from less than 1% to 33% have been reported for bottom ash from pulverized-coal-fired boilers using eastern coal (28), considerably higher than that of fly ash from the same units.

Bottom ash is reasonably well graded, with particle sizes ranging from fine sand to coarse gravel. Most particle sizes fall in the range of fine gravel to medium-fine sand (10 to 0.2 mm, or 3/8 to 1/16 inch). Specific gravities of 2.3 to 2.8 have been reported for bituminous coal bottom ash from dry bottom furnaces (50); the higher specific gravities were attributed to high iron contents. Others (51) report bottom ash specific gravities of 2.1 to 2.5. In comparison, silica sand has a density of about 2.6. Compacted bulk densities of 50 lb/ft^3 to over 100 lb/ft^3 have been reported.

Angles of internal friction on the range of 30° to 40° have been reported, values similar to those of sand and gravel. Uniaxial compression tests also show a behavior similar to sand. The permeability of bottom ash is in the range of 10^{-1} to 10^{-2} cm/sec, again in the range of sand. The permeability is relatively unaffected by compaction, compared with fly ash (34).

ASH HANDLING

Ash handling and disposal consists of removal of the ash from the bottom ash hoppers, the economizer, air heater, and other auxiliary hoppers, and from the ESP fly ash hoppers; transport of the ash through various intermediate collection and storage facilities to final disposal, or directly to final disposal; and management of the disposal sites. A variety of methods may be used to accomplish these tasks (38). These combine with individual design variations (53) to produce what is essentially a unique system, adapted to each power station's fuel and boiler characteristic and disposal requirements. Within this diversity, however, distinctive general patterns exist, particularly for large, new central stations, that characterize utility ash disposal methods.

Fly Ash

Inverted pyramidal hoppers that form the bottom of the collection device are usually used to collect the fly ash. Fly ash is usually hygroscopic to some degree and the flue gas atmosphere usually has a sulfuric acid dewpoint of about 250°F and a water dewpoint of about 150°F. Packing, caking, and cementitious reactions can be a major problem if the ash is allowed to cool below these dewpoints (54). The hoppers are often insulated and heat traced to prevent this.

Fly ash is normally removed from the hoppers on an intermittent basis using a pneumatic conveying system. Vacuum systems using a hydraulic ejector in which the ash-air mixture is drawn directly into the ejector are common. The resulting ash slurry, composed of 5% to 10% solids, can be pumped or can flow by gravity directly to dewatering or final disposal ponds. Vacuum systems using vacuum pumps in which the ash is collected in mechanical separators and fabric filters are also used. Vacuum systems are limited to a few hundred feet of length and their efficiency is reduced at high altitudes. Pressure systems may be used, alone or in conjunction with vacuum systems, for higher capacities or longer distances. Ash-to-air weight ratios vary, depending on the system from over 30 to 1 to about 6 to 1. Velocities vary from about 300 ft/min to a few thousand ft/min.

Fly ash collected by direct ingestion in hydraulic ejectors is usually sluiced to ponds of several years' capacity rather than short-term dewatering ponds. Fly ash collected in silos may also be reslurried and pumped to a pond although it is more frequently moistened for dust control and hauled to a disposal site. The silos are often elevated for direct loading through a moisturizer into rail cars or trucks.

Bottom Ash

Bottom ash hoppers usually have a capacity of several hours. The ash level is monitored with instruments or visually and the hoppers are emptied either as necessary or on a working-shift time basis. In most cases a hydraulic sluicing system is used. The ash door to the clinker grinder is opened and the ash is flushed through the clinker grinder and into the transportation pump with high pressure water jets mounted inside the hopper.

Either water ejector pumps or centrifugal pumps are used. Ejector pumps are simpler to service though less efficient and limited in pumping head. If a centrifugal pump is used water is added at the suction to dilute the slurry and at the bearings to prevent erosion. Slurry concentrations of 1% to 5% are most common. Velocities in the range of 10 ft/sec are necessary to keep the ash in suspension. Remixers or agitators every few thousand feet may also be necessary.

The subsequent handling of the bottom ash is largely a matter of site-specific circumstances. The ash may be pumped to a disposal pond, to a dewatering pond, or to dewatering tanks. The disposal system may also be combined with other disposal systems. Mill rejects (also called pyrites), the noncoal mineral waste collected from the pulverizers, and economizer ash are frequently transported in the bottom ash system. Hydraulically collected fly ash may also be transported in the same lines.

Along with pumps and ejectors, transport lines suffer from high wear rates because of the abrasive bottom ash. Hard steel pipe and fittings, basalt and ceramic liners, and replacable wear plates are frequently used to reduce wear. Pipes are also rotated to equalize wear.

Commercial equipment specifically designed for utility ash handling is available from a number of suppliers (53), some of whom offer European designs little used in the United States. In particular a low-headroom bottom ash system called the submerged scraper conveyor or submerged drag bar chain conveyor (55) and dense-phase pneumatic systems (56) have received attention. The former is common in Europe. The bottom ash falls from the furnace into a shallow flat-bottom hopper filled with water. It is continually removed by a drag conveyor which operates horizontally and submerged in the hopper, then upward along an inclined dewatering trough. Depending on subsequent needs, the ash may be crushed and trucked or sluiced from the surge hopper to disposal.

Ash Disposal

Several general or specific surveys of ash disposal methods have been made. One of the most comprehensive is that by Versar, Inc., for EPA (57) in which over 200 power-plant ash disposal practices were surveyed. Radian Corporation (58) conducted a similar survey. More commonly, specific sites or aspects of specific sites are reported (59).

Transportation of ash to disposal or storage sites is decidedly a site-specific operation. Sluicing to diked ponds for either final disposal or temporary storage is common, as is trucking to captive or commercial landfills. Not uncommonly, particularly with bottom ash, the ash is removed from settling ponds and landfilled or utilized. Trucking by a variety of on-road and off-road designs is the most common method of dry ash transportation. Both captive and contract trucking operations are employed. On the average, the distance to the disposal site is short, averaging about three miles with over nine-tenths under five miles (60). Exceptions exist, however, particularly when trucking is used because land is not available in the vicinity of the power plant.

Ponding of sluiced ash is a common practice used in one form or another by more than half of the U.S. utilities (58), most commonly by those east of the Mississippi River (57). In most cases the fly ash and bottom ash are sluiced directly to separate or combined final disposal ponds. In some cases the ash is removed and landfilled, either as a planned procedure or as an expedient to extend the pond life. Temporary ponding is used more frequently for bottom ash than for fly ash. A substantial percentage of utilities use dry handling and landfill for fly ash and temporary or permanent bottom ash ponding. In lieu of temporary ponds mechanical dewatering systems may be used for bottom ash.

Ponds differ greatly in design and capacity. Usually earthen dikes are used, frequently incorporating natural topography or manmade excavations such as quarries to form a part of the impoundment. Pond lives range from a few years to well over 30 years. Pond depths are generally in the range of a few dozen feet. Some, incorporating topography in hilly terrain may have depths of over 100 feet, however. Most ponds now in use are not lined in the sense that synthetic or imported earthen materials were emplaced.

Landfills share with ponds a heterogeneity of type and size, use of manmade and natural features, and other characteristics of morphology and development. Landfills range from structured constructions to back dumping in convenient depressions or excavations. As with ponds, topography often serves to define the form and structure of landfills. Unlike ponds, however, landfills show no strong climatically related distribution. The choice of landfill disposal may be the result of lack of nearby land or lack of sufficient water for sluicing. Not uncommonly, power plants supplied by nearby surface mines dispose of ash in the mined-out area.

Further complicating the characterization of ash disposal practices are variations in ash utilization practices. In a few cases ash is routinely sold or given away to commercial operations. In others, however, ash is intermittently sold or given away as temporary outlets occur. Sometimes appreciable quantities are thus disposed of in a short time, altering the normal power-plant disposal practices (60).

Ash disposal practices, as represented by operating power plants in the late 1970's, are dictated by many factors. Among these are availability of water, availability of land, local and state regulations, topography, geology, utility experience, and availability of utilization outlets. All of these in their many combinations act to produce highly individualistic disposal practices. In some cases different methods may be employed at the same site, in others practices may change with time. Ponding of hydraulically transported ash, ponding followed by excavation and landfill, and direct landfill of dry ash, all in numerous variations, are the primary methods of current ash disposal practices. In addition, a minor to major portion of a particular power plant's ash may be routinely or intermittently sold or given away for utilization.

Several factors will tend to alter future disposal practices. Paramount among these are environmental regulations affecting ash disposal primarily through restrictions on pollution of surface and ground water. Other factors may also be influential, among them a diminishing availability of land, increasing construction of power plants in dry climatic zones, and increasing sophistication of ash utilization. Among the practices likely to be influenced are methods that discharge suspended and dissolved material to surface and ground waters, methods that cause cementitious reactions that hinder disposal operations, and methods that reduce the usefulness and therefore the utilization of the ash.

WASTE DISPOSAL REGULATIONS

Disposal of power plant ash, along with other power plant wastes, may be subject to numerous Federal, State, and local regulations. These are administered by several agencies, and pertain to various aspects of industrial health and safety in addition to environmental considerations. Santhanam and others (61) discuss the regulatory structure of power plant waste and water management. Rice and Strauss (62) discuss power plant water pollution control.

The disposal of power plant ash in ponds and landfills is primarily affected at the Federal level by the Clean Water Act (CWA) and the Resource Conservation and Recovery Act (RCRA) of 1976. Other disposal methods such as well injection and mine disposal are affected by other Federal regulations as well. Since one of the primary intents of these laws is the encouragement of State programs, much of the legislation directly affecting ash disposal is in the form of minimum standards and guidelines. It thus represents standards that may be superseded by more extensive or stricter regulations in particular applications (63).

The CWA requires establishment of procedures and regulations to control discharge of pollutants into navigable waters. Under it, the National Pollution Discharge Elimination System (NPDES) was established. This requires a permit for each point source discharge into navigable waters. The permit establishes specific pollutant concentrations and monitoring requirements for the source that it applies to. Although emphasis, particularly in the 1977 amendments, has been placed on toxic pollutants, initial guidelines were for so-called conventional pollutants such as suspended solids, oil and grease, and sewage-derived materials, and for extreme pH's. When EPA promulgated effluent guidelines and standards for power plants (64,65), criteria for total suspended solids (TSS), oil and grease, and pH were established for ash transportation water and ash disposal site runoff. These require best available technology economically achievable (BAT) for existing sources to be attained by 1984 and using new source performance standards (NSPS).

	Average mg/l	
	BAT	NSPS
Bottom ash transportation water		
TSS	30	30
Oil and grease	15	15
Fly ash transportation water		
TSS	30	None
Oil and grease	15	None
Runoff		
TSS	50	50
pH, all discharges	6-9	6-9

More recently EPA established proposed effluent standards (66) for some toxic pollutants, including a number of ash trace elements, that are to be incorporated into NPDES permits.

RCRA has been generally described in journals (67). The law amended existing Federal solid waste laws with the stated objective of protecting public health and the environment and encouraging conservation of national resources, primarily through the encouragement and support of State regulatory programs and conservation measures. Attention primarily focused on Subsection C of the law, which establishes a regulatory program for hazardous wastes, and Subtitle D, which provides for Federal assistance to States in the management of nonhazardous wastes. Subtitle C in particular provides for strict and extensive minimum standards on the handling and disposal of materials designated as hazardous by criteria established by EPA.

In 1978 and 1979 (68,69) EPA published proposed rules for control of hazardous wastes under Subtitle C. In these, utility wastes, including ash and FGD waste were, among others, classified as special wastes subject to Subtitle C regulations at least in part. The stated purpose of this classification was to permit time for further study of the nature of these wastes, for which limited information existed. In placing these wastes in this special category, EPA indicated that they were not certain what percentage was, in fact, hazardous. Inclusion of utility wastes in this category created some misinformation and considerable distress among those concerned with these wastes (70). Utilities already struggling with relatively new technologies to cope with environmental regulations were concerned with the prospect of much more rigid and expensive control. To others, the prospect of a hazardous waste stigma becoming attached to materials that they were attempting, with some success, to promote as useful raw materials was equally disturbing (71).

Some studies were already in progress to characterize the behavior of utility ash wastes and waste monitoring requirements. Radian Corporation (72) reported on studies of trace element behavior in ash pond leachates. Theis (73) made a field study of ash pond leachate. EPA and TVA began studies to characterize coal-fired utility plant effluents in the late 1960's, such as ash pond effluent monitoring reported by Miller and others (74) and the ash studies of Ray and Parker (29). Other studies were initiated or shaped, at least in part, by RCRA. EPA initiated a program to develop information on utility ash disposal, including the survey of existing practices by Versar, Inc., (57), who gathered information from about two-thirds of U.S. utility power plants. Engineering-Science (10) conducted a study on ash disposal costs of representative U.S. utilities as part of a continuing study by the Department of Energy. This study evaluated disposal methods and costs for application of RCRA hazardous and nonhazardous alternatives. The hazardous waste regulations used in this study were based on the original regulations proposed in 1978 (68). EPRI has sponsored studies to review the relationship of utility waste characteristics to RCRA requirements such as that by Fred C. Hart Associates, Inc., (22) and to summarize existing data on utility solid wastes (23). The EPRI Fly Ash Structural Fill Handbook (36) and Ash Disposal Reference Manual (75) also pertain directly to current ash disposal requirements.

Early in 1980 EPA began promulgating final regulations on much of the RCRA Subsection C hazardous waste regulations (76,77). Among these (77, p. 33120) were exclusions for "fly ash waste, bottom ash waste, slag waste, and flue gas emission control waste generated primarily from the combustion of coal or other fossil fuels." The rationale for this exclusion (77, pp. 33173-33175) was relaxation of the definition of properties that would bring these materials into Subtitle C, increased flexibility in Subtitle C waste management requirements, and anticipation of Congressional action which would defer the regulations for utility wastes, among others. Later in 1980 an EPA study was established by congressional mandate to study coal combustion wastes. This study is being conducted by Arthur D. Little, Inc. In the meantime, these wastes are excluded from both Subtitles C and D of RCRA.

Subtitle D of RCRA, State and Regional Solid Waste Plans, is directed to the control of nonhazardous waste disposal methods through the establishment of minimum criteria and the encouragement of State and regional management plans. EPA promulgated these criteria in 1979 (78). The criteria establish minimum standards for classification of a disposal facility as a sanitary landfill. Those facilities not meeting the criteria are by definition open dumps, which are prohibited by RCRA. There are numerous exclusions for activities and substances controlled by other regulations, including point source discharges subject to NPDES permits. The criteria are general in nature and focus on protection of sensitive areas, groundwater, surface water, and air qualities. Details of preferred methods of operation are not specified. Among the criteria most pertinent to utility ash disposal are floodplain, wetland and endangered species habitat, siting restrictions, and limitations on groundwater and surface water contamination.

The manner in which Subtitle D criteria will affect utility ash disposal practices has not been fully assessed. The effects are likely to be varied, particularly since State regulations vary and other Federal environmental legislation will also affect changes in existing practices. Engineering-Science found that most States report that the majority of existing sites meet Subtitle D requirements, a view contrary to the survey of Engineering-Science (10). Provisions of the Clean Water Act such as NPDES will also alter current water use practices such as once-through use of water in sluicing. The general field of water reuse is widely discussed (79). Chu and others (80) and Noblett and Christman (81), among others, discuss water reuse in utility waste applications.

LEACHATE

Both field and laboratory studies of ash leachate have been made. These have been summarized by Fred C. Hart Associates (22), Radian (23), and GAI Consultants (36), among others. Theis and others (73) studied trace elements in ground water around an ash pond. Miller and others (74) conducted a study of ash pond effluents. Radian (72) conducted laboratory studies of trace elements in fly ash and bottom ash leachates, including attenuation by seepage through clay soils. Ash leachates are generally alkaline although some are acidic. Some ash pond effluents require pH adjustment to meet the NPDES maximum of 9.0 (57). The water-soluble fraction of bituminous fly ash ranges from minor to several percent. Typically calcium and sulfate are the major dissolved species, along with aluminum, iron, silica, magnesium, sodium, and potassium in the range of several ppm and sometimes chloride in the range of 100 ppm. Most of the trace elements found in the ash are usually identified at low levels. The level and composition of dissolved solids depend on many factors other than ash composition, including the pH, leachate volume, equilibrium relationships, and attenuation by soil and dissolved species from the ash such as iron and magnesium. Radian (72) found a considerable attenuation by clay-containing soils. Theis and others (73) found similar attenuations in field studies, as well as concentration excursions related to operational variations such as pond filling rates. Generalization of ash leachate characteristics in disposal sites is further complicated by the previous handling history, such as sluicing and temporary ponding, cementitious reactions, inclusion of other power plant wastes, and seepage rates.

ASH UTILIZATION

Coal ash, along with other types of similar ashes and slags, has long found widespread if limited use, primarily as structural fills and bases and as an aggregate in concrete and bituminous surfaces. These continue to be the primary uses.

Table 1 shows utility ash production and use patterns for 1977. About one-fifth of the ash produced was utilized, mostly for concrete aggregate and road construction, either directly or after disposal. Fly ash represents the largest quantity used but the smallest percentage in terms of quantity produced. Boiler slag, mostly the shattered slag from wet bottom furnaces, has the highest utilization rate. It is composed of large dense particles that can be conveniently crushed to make sized aggregate and grit for coatings and other uses.

In recent years the use of ash has been extensively studied, promoted, and broadened. The proceedings of the ash utilization symposiums sponsored by the National Ash Association (82,83,84) illustrate the scope of these efforts. Much effort in ash utilization continues to be directed toward conventional uses. Many studies consist of evaluations of ash in concrete, concrete products, and in structural fills. In addition, there is an increasing effort to establish criteria and standards for ash properties to legitimate its credentials as a construction material. Increasingly, however,

TABLE 1. ASH COLLECTION, UTILIZATION, AND DISPOSAL, 1977

	Fly ash		Bottom ash		Boiler slag		Total[a]	
	10^6 tons	%	10^6 tons	%	10^6 tons	%	10^6 tons	%
Collection								
Ash collected	48.5	71.5	14.1	20.8	5.2	7.7	67.8	100.0
Utilization								
Direct usage								
Cement	2.3	37	0.1	2	0.1	3	2.5	18
Road construction	1.7	27	1.3	28	0.3	10	3.3	24
Ice control	-	-	1.0	22	0.4	13	1.4	10
Roofing	-	-	-	-	1.5	48	1.5	11
Miscellaneous	0.2	3	0.4	9	0.7	22	1.3	9
Removed from site at no cost to utility	0.4	7	0.8	17	0.1	4	1.3	9
Utilized from site after disposal cost was incurred	1.6	26	1.0	22	-	-	2.6	19
Total	6.3	100	4.6	100	3.1	100	14.0	100
Percent utilization	13.0%		32.6%		60.0%		20.7%	
Disposal								
Permanent disposal	42.2	78.4	9.5	17.7	2.1	3.9	53.8	100.0
Disposal for utilization	1.6	61.5	1.0	38.5	0	0	2.6	100.0
Total	43.8	77.7	10.5	18.6	2.1	3.7	56.4	100.0
Disposal for utilization as % of ash collected	3.4%		7.1%		0.0%		3.8%	
Disposal as % of ash collected	90.3%		74.5%		40.4%		83.2%	

a. Adapted from data by the National Ash Association.

more specific and exotic uses have been advanced. Use of cenosphere fractions as fillers, the use of the magnetic fraction for heavy medium separations, and recovery of metals such as aluminum or trace elements have been advanced. The use of fly ash in flue gas desulfurization processes either as an absorbent or absorbent amendment (85) or more frequently as a waste stabilization additive (86) is also growing.

The quantity of ash utilized has consistently grown for many years as a result of these and other applications. At the same time, however, the quantity of ash produced has grown. Consequently, as the percentage of ash utilized has increased so has the quantity disposed of, as shown in Figure 3. Both utilization and disposal are likely to remain important for many years. The growing emphasis and increasing specialization of ash utilization may, however, have important effects on ash collection, handling, and disposal. Specialized uses requiring particular physical or chemical properties, such as particle size or chemical reactivity, could dictate specific collection, handling, and storage methods. It has been suggested, for example, that utilities consider utilization requirements as a factor in boiler design (4).

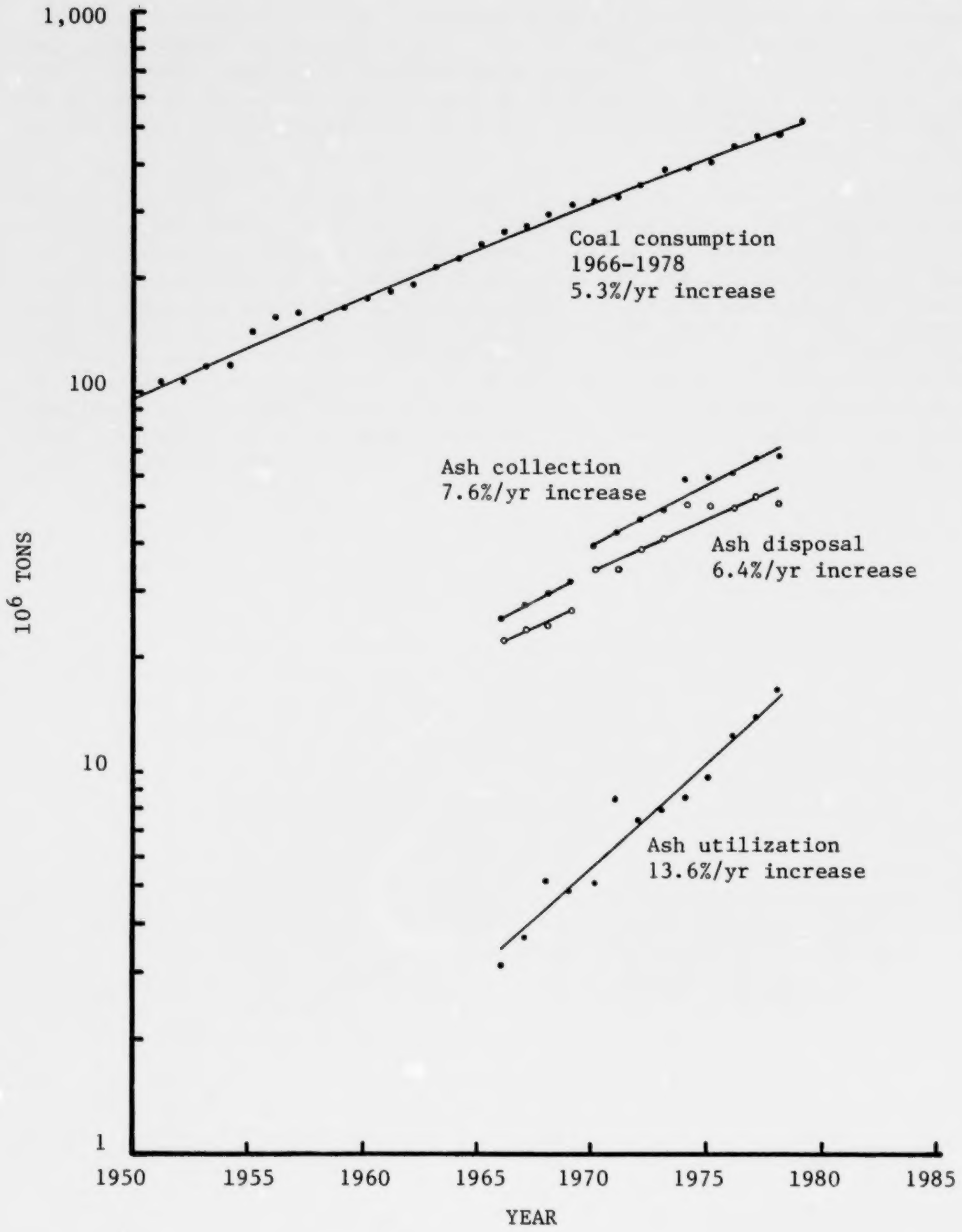

Figure 3. Utility coal consumption, ash production, and ash utilization - 1950-1978. (data from Faber, J. H., Ref. 71)

PREMISES

The design and economic conditions used in this study to evaluate the economics of ash disposal are based on premises developed by TVA in 1979 for evaluations of this nature. The premises are designed to represent current industry conditions and to provide equitable cost comparisons in significant and useful divisions. TVA has used similar premises for EPA-sponsored economic studies made for the past dozen years. The premises used in this study are revisions of premises used during the late 1970's, updated to reflect design, economic, and regulatory conditions of the 1980's.

DESIGN PREMISES

The utility plant design is based on Department of Energy (DOE) historical data (87), general industry information, and TVA experience. The conditions are representative of a typical modern pulverized-coal-fired boiler for which current emission control practices would be most likely applied. A midwestern location is used because of the concentration of power plants and the diversity of coals used for fuel in this area.

Environmental Standards

The NSPS established by EPA in 1979 for particulate matter, SO_2, and NO_x emissions, specify a maximum emission, based on heat input, of 0.03 lb/MBtu for particulate matter. This removal efficiency is used for this study. ESP's with removal efficiences above 99% are assumed to be the collection method. To facilitate cost comparisons the same SCA is used for both coals. It is also assumed that other emission requirements are met by methods independent of, and having no economic effect on, ash collection and disposal.

Except for base cases 1 and 3 disposal sites are assumed to be governed by the NPDES, NSPS, and RCRA Subtitle D guidelines. Base cases 1 and 3 are assumed to be governed by NPDES BAT requirements. It is assumed that no treatment or specific controls for excessive levels of nonconventional pollutants other than a liner is required. (A liner is not a regulatory requirement.)

Fuel

The coal characteristics are composites of published data on utility coal compositions. They represent types of utility coals expected to be in general use in the early 1980's (9,88,89). The eastern coal composition is an average of coals from the Appalachian region and the Illinois basin. The western coal composition is a similar average of western coals, not all of which are subbituminous, from various coal fields that supply utilities in the West and Midwest. The coal compositions are shown in Table 2.

TABLE 2. COAL COMPOSITIONS

	Wt % as fired	
Component	High-sulfur eastern	Low-sulfur western
C	66.7	57.0
H	3.8	3.9
O	5.6	11.5
N	1.3	1.2
S	3.36	0.59
Cl	0.1	0.1
Ash	15.1 (2% Ca)	9.7 (10% Ca)
Moisture	4.0	16.0

Ash compositions are based on averages of ash compositions typical of the coals used. With the exception of calcium content the compositions are not qualified in terms of physical and chemical behavior. Both ashes are assumed identical in handling properties until wetted. The eastern coal ash is assumed to have no cementitious self-hardening properties affecting handling and disposal site emplacement. The western coal ash is assumed to have self-hardening characteristics that affect handling and emplacement within a few hours after being wetted.

Flue Gas Composition

Combustion and emission conditions used to determine flue gas composition are based on boiler design and the coal compositions listed in Table 2. Flue gas compositions are based on combustion of pulverized coal using a total air rate equivalent to 139% of the stoichiometric requirement. This includes 20% excess air to the boiler and 19% air inleakage in the boiler air heater, which reflect operating experience with horizontal, frontal-fired, coal-burning units. It is assumed that 80% of the ash present in the coal is emitted as fly ash and 85% and 92% of the sulfur in the coal is emitted as SO_x for the western and eastern coals respectively. The base case flue gas composition and flow rates calculated for these conditions are shown in Table 3.

TABLE 3. BASE CASE FLUE GAS COMPOSITIONS AND FLOW RATES

Flue gas component	Eastern coal, 3.5% S Volume, %	 Lb/hr	Western coal, 0.7% S Volume, %	 Lb/hr
N_2	75.21	3,851,000	73.09	3,887,000
O_2	5.54	323,900	5.39	327,200
CO_2	12.34	992,300	12.24	1,023,000
SO_2	0.20	24,330	0.04	4,760
SO_3	0.01	940	-	184
NO_x	0.03	1,908	0.03	1,590
HCl	0.01	418	0.01	504
H_2O	6.66	219,100	9.20	314,600
Ash	-	49,040	-	38,000
Total	100.00	5,463,000	100.00	5,597,000

Power Plant

A single horizontally fired, dry-bottom, balanced-draft boiler with a 500-MW adjusted gross electrical output is used. The adjusted gross output is not derated for the electrical consumption of the ash disposal systems. This electricity is costed as purchased electricity to provide the same basis of comparison in terms of electrical output.

The power plant is assumed to have a 30-year lifetime during which it operates the equivalent of 165,000 hours at full load. A yearly operation of 5,500 hours at full load is assumed. All costs are based on full-load operation. A heat rate of 9,500 Btu/kWh is used for both coals. Ash rates are based on the as-fired ash content of the coal, assuming a ratio of 20% bottom ash and 80% fly ash with no adjustment for pulverizer rejects or slagging and fouling losses.

Ash Collection and Transportation

The designs used in development of the ash disposal systems are based on use of standard components used by the utility industry and available from equipment suppliers. The design and construction of the systems is assumed to be integrated with the overall power plant design and construction. The ash collection systems begin with the bottom ash and fly ash hoppers that receive the ash from the boiler and the flue gas trains. All hopper, ash collection and temporary storage, transportation, and disposal costs are included in the overall ash disposal costs.

The following dry bulk densities and water contents are used.

	% moisture					Dry bulk density, lb/ft^3
Base case:	1	2	3	4	5	All
Ash in hoppers						
Fly	0	0	0	0	0	50
Bottom	-	-	-	-	-	45
Ash in pipelines						
Fly	92.3	92.3	92.3	-	-	-
Bottom	92.3	92.3	92.3	83.3	83.3	-
Ash in trucks						
Fly	-	-	25	10	0	80
Bottom	-	-	10	10	10	80
Ash in ponds						
Fly	47	47	47	-	-	55
Bottom	47	47	47	-	-	55
Ash in landfills						
Fly	-	-	17	17	17	90
Bottom	-	-	17	10	10	90

Disposal Sites

The disposal sites are sized for the life of the power plant. All land is assumed purchased at the start of the project. All development costs associated with the ponds and landfills are capitalized at the beginning of the project. These include all construction which establishes or extends the capacity of the facility such as clearing, topsoil removal, lining, grading, dike construction, fencing and construction, and reclamation. Normal area-fill landfill operational procedures are used, with topsoil removal, lining, and reclamation proceeding during the course of its life.

In addition to the land occupied by the ponds or landfills, land is provided for topsoil storage, working and maintenance functions, runoff control, a 50-foot security perimeter, and roads. A 6-foot security fence, lighting, and monitoring wells are also provided. Provisions are included for reclamation that consists of topsoil replacement and revegetation.

Ponds consists of square excavated basins surrounded by earthen dikes constructed of subsoil removed from the impoundment area. The depth and area of the pond are calculated to minimize the sum of land and construction costs. A typical pond cross-section is shown in Figure 4. Clearing is assumed to be removal of a light growth of submature trees and grubbing. A 1-1/2-foot layer of surface soil is removed and stockpiled. The dikes have a stone-lined interior face, a graveled roadway on the top, and a topsoiled and revegetated outer face. A diverter dike of similar construction extends three-fourths of the pond width from one side to increase the flow distance from the inlet to the overflow. A 1-foot-thick liner of compacted clay (not required by regulations) is placed on the pond bottom and the interior faces of the dikes. The clay is assumed locally available but to require hauling in the course of placement.

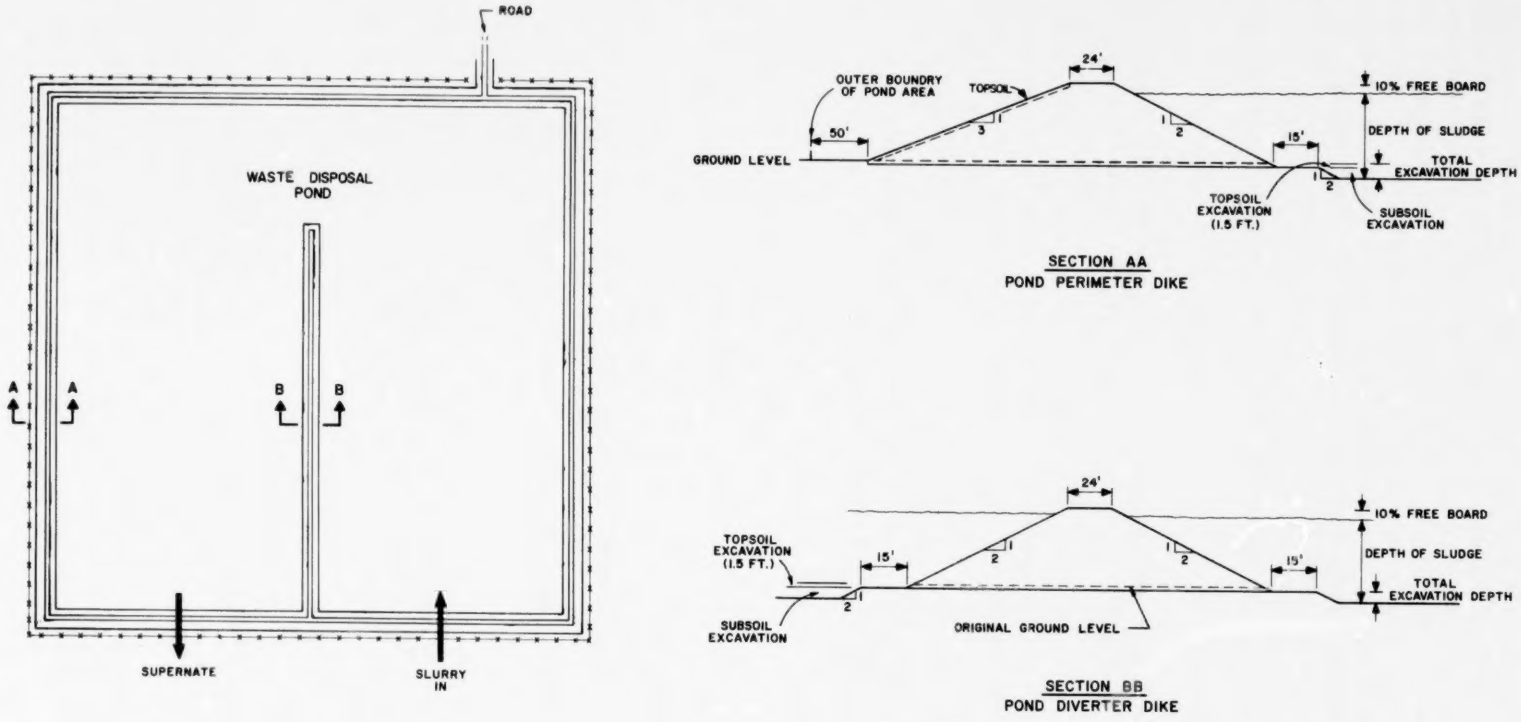
ROAD
WASTE DISPOSAL POND
A
A
B
B
SUPERNATE
SLURRY IN
OUTER BOUNDRY OF POND AREA
TOPSOIL
24'
10% FREE BOARD
50'
3
1
1
2
DEPTH OF SLUDGE
GROUND LEVEL
15'
TOTAL EXCAVATION DEPTH
1
2
TOPSOIL EXCAVATION (1.5 FT.)
SUBSOIL EXCAVATION
SECTION AA
POND PERIMETER DIKE
24'
10% FREE BOARD
TOPSOIL EXCAVATION (1.5 FT.)
15'
2
1
1
2
15'
DEPTH OF SLUDGE
TOTAL EXCAVATION DEPTH
2
1
SUBSOIL EXCAVATION
ORIGINAL GROUND LEVEL
SECTION BB
POND DIVERTER DIKE

Figure 4. Pond dike construction details.

The landfills are prepared, filled, and covered in increments of area to form, when completed, a square area-type fill with an edge height of 20 feet and a maximum height at the center of 60 feet. A typical landfill cross section is shown in Figure 5. The sides have a slope of 1 vertical to 2 horizontal and the top slopes up to the center at 2° (35 feet per 1000 feet). The landfill is surrounded by a 24-foot-wide perimeter ditch that drains to a catchment basin for runoff control and monitoring. A 1-foot-thick clay liner and a 2-foot-thick porous base of bottom ash that drains to the catchment basin are provided. Reclamation consists of placing 1-1/2 feet of surface soil over the completed portion of the landfill and revegetation.

Mobile Equipment

Mobile equipment requirements are based on the quantity, moisture content, and bulk density of the ash and truck specifications and operating profiles established for the specific operating conditions. Mobile equipment operating data were obtained from published sources and information obtained from manufacturers and suppliers. The truck sizes were selected to provide flexibility of operation and a compromise of capital and operating costs for the volume of ash involved. One spare truck is provided for each trucking operation. Cycle times are based on a road speed of 30 mph for the specified distance to the disposal site (0.75 mile for base case 3 and 1 mile for base cases 4 and 5), an onsite speed of 15 mph, and estimated times for loading, spotting, and dumping based on the type of ash:

Base case:	3	4	5	
			Fly ash	Bottom ash
Distance, mi	1.5	2.0	2.0	2.0
Road time, min	3	4	4	4
Off-road time and miscellaneous, min	33	24	52	22
Total, min	36	28	56	26

Truck requirements for different ash quantities and cycle times are shown in Figure 6. The requirements are based on 20-yd^3-capacity trucks operating 16 hr/day during the power plant operating year of 5500 hr with 1 spare truck per 2 trucks and ash with a dry bulk density of 1.08 tons/yd^3.

ECONOMIC PREMISES

The economic premises establish criteria to determine capital costs for construction of the ash disposal system and annual revenue requirements for its operation. The premises are based on regulated utility economics and use the design premises as a costing basis. The estimates use cost information obtained from engineering-contracting and equipment companies and published cost indexes. Equipment and labor costs are assumed equivalent to those in the Midwest for all coal cases.

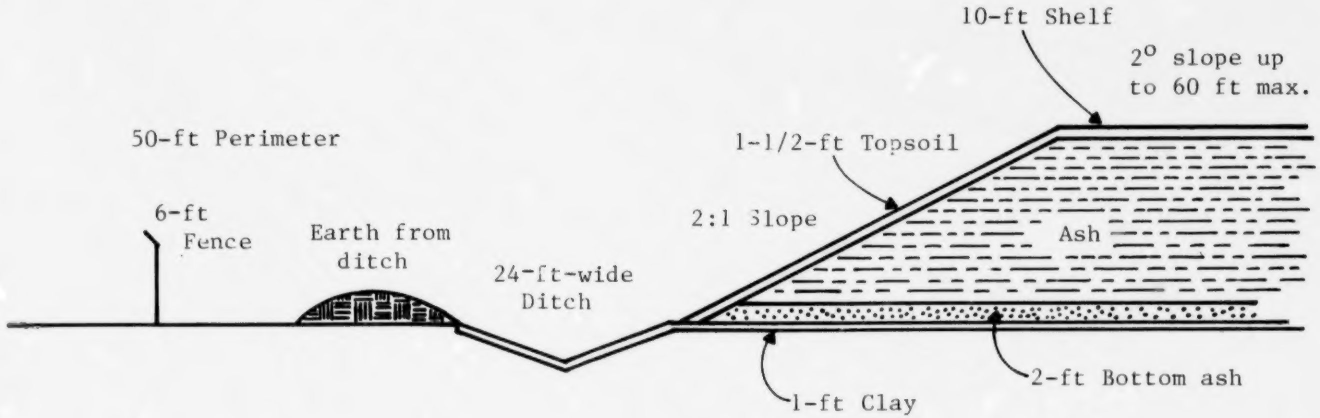
10-ft Shelf
2° slope up to 60 ft max.
50-ft Perimeter
1-1/2-ft Topsoil
6-ft Fence
Earth from ditch
2:1 Slope
Ash
24-ft-wide Ditch
2-ft Bottom ash
1-ft Clay

Figure 5. Landfill construction details.

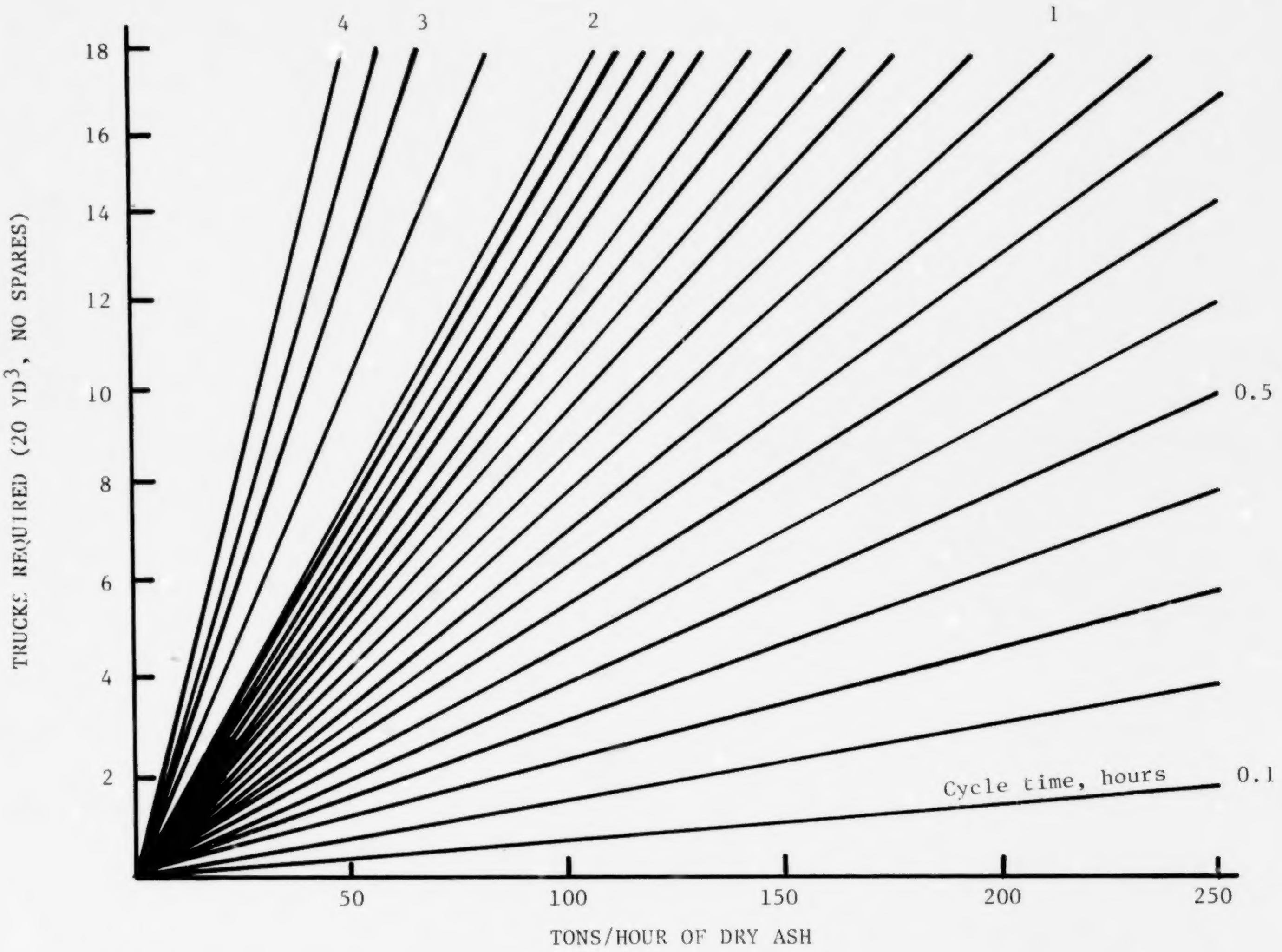

Figure 6. Truck requirement for ash transportation.

Capital Investment Estimates

Capital investment estimates for this study represent projects beginning in early 1981 and ending in late 1983. Capital cash flows are assumed to be 25% in the first year, 50% in the second year, and 25% in the third year of the project life. Capital costs for fixed assets are projected to mid-1982, which represents the approximate midpoint of the construction expenditure schedule. The estimates in this study are based on a process description, flowsheet, material balance, and equipment list with sizing and materials of construction. Other costs are scaled from the equipment costs. These study-level estimates are considered to have a -20% to +40% range of absolute accuracy and a relative accuracy for comparison between systems of approximately 10%.

The total fixed capital investment consists of direct capital investment for equipment, its installation, and its service facilities, indirect capital investment for engineering, contracting, and construction expenses, and contingency. The total capital investment consists of the total fixed capital investment plus allowances for startup and modifications, royalties, the cost of funds during construction, and the cost of land and working capital.

Direct Capital Investment--

Direct capital investment covers process equipment, piping, insulation, transport lines, foundations, structures, electrical equipment, instrumentation, site preparation and excavation, buildings, roads, trucks, and earthmoving equipment. Direct investment costs are prepared using the average annual *Chemical Engineering* cost indexes and projections as shown below:

Year	1978	1979[a]	1980[a]	1981[a]	1982[a]	1983[a]	1984[a]
Plant	218.8	240.2	259.4	278.9	299.8	322.3	344.9
Material[b]	240.6	262.5	286.1	309.0	333.7	360.4	385.6
Labor[c]	185.9	209.7	226.5	244.6	264.2	285.3	305.3

a. TVA projections.
b. Same as index in *Chemical Engineering* (92) for "Equipment, machinery, supports."
c. Same as index in *Chemical Engineering* (92) for "Construction labor."

The overtime premium for 7% overtime is included in the construction labor. Appropriate amounts for sales tax and for freight are included.

Costs for ponds and landfills are calculated using the cost factors shown in Table 4.

TABLE 4. POND AND LANDFILL UNIT COSTS

	1982 $
Clearing	904.00/acre
Clay liner	3.50/yd^3
Revegetation	0.70/yd^2
Removal or replacement topsoil	2.68/yd^3
Coarse gravel	11.37/yd^3
Discharge channel	29.16/ft
Access road	5.05/ft
Security fence	17.50/ft
Monitoring wells	1,166.00 each
Office trailer	29,160.00 each
Dike construction	2.33/yd^3
Underdrain blanket	0.00/yd^3

Necessary electrical substations, conduit, steam, process water, fire and service water, instrument air, chilled water, inert gas, and compressed air distribution facilities are included in the utilities, services, and miscellaneous direct investment. These facilities are costed as increments to the facilities already required by the power plant. Service facilities such as maintenance shops, stores, communications, security, offices, and roads are estimated on the basis of process requirements. Services, utilities, and miscellaneous costs will normally be in the range of 4% to 8% of the total process capital depending on the type of process. A 4% rate is used in this evaluation for all processes.

Indirect Capital Investment, Contingency, and Other Capital Investment--

Indirect capital investment covers engineering design and supervision, architect and engineering contractor costs, construction costs, and contractor fees. Construction facilities (which include costs for construction mobile equipment, temporary lighting, construction roads, raw water supply, construction safety and sanitary facilities) and other similar expenses incurred during construction are considered as part of construction expenses and are charged to indirect capital investment. A contingency of 10% is included. The contingency is calculated as a percentage of the sum of the direct and the indirect investments, less mobile equipment costs. Startup and modification allowances are estimated at 8% of the total fixed investment related to process equipment.

Interest during construction is 15.6% of the total fixed investment excluding mobile equipment. This factor is equivalent to the 10% weighted cost of capital assuming 25% of the construction expenditures in the first year, 50% the second year, and 25% the third year of the project construction schedule. Expenditures are assumed uniform over each year. Startup costs are assumed to occur late enough in the project schedule that there are no charges for the use of money used to pay startup costs.

The percentages used for each type of proportioned investment are shown in Table 5.

TABLE 5. PERCENTAGE FACTORS FOR PROPORTIONED INVESTMENTS

	Mobile equipment	Process	Pond	Landfill
	% of direct investment			
Indirect Investment				
Engineering design and supervision	0	6	2	6
Architect and engineering contractor	0	3	1	3
Construction expense	0	10	8	10
Contractor fees	0	6	5	6
Total indirect investment	0	25	16	25
	% of direct and indirect investment			
Contingency	0	10	10	10
	% of total fixed investment			
Other Investment				
Allowance for startup and modifications	0	8	0	0
Interest during construction	0	15.6	15.6	15.6

Working capital is the total amount of money invested in process reagents, supplies, accounts receivable, and monies on deposit for payment of operating expenses. Working capital is calculated as the equivalent of 1 month's process reagents, 1.5 months' conversion cost, and 1.5 months' plant and administrative overhead costs. In addition, it includes an amount equal to 3% of the total direct investment, excluding pond and landfill, to cover spare parts, accounts receivable, and monies on deposit to pay taxes and accounts payable.

Annual Revenue Requirements

Annual revenue requirements use 1984 costs and are based on 5,500 hours of operation per year at full load. Both first-year and levelized annual revenue requirements are determined. Levelized annual revenue requirements are based on a 10% per year discount factor and a 6% per year inflation rate over the 30-year life of the power unit. Direct costs consist of raw materials, labor, utilities, maintenance, and analytical costs. Indirect costs consist of overheads and levelized capital charges.

Direct Costs--

Projected process reagent, labor, and utility costs are listed in Table 6. Unit costs for electricity are based on the assumption that the required energy is purchased from another source. Unit costs ($/kW, mills/kWh) are calculated on the basis of adjusted gross power output of the boiler excluding the electricity consumed by the ash disposal systems. Actually, electrical use by the ash disposal system will result in a derating of the utility plant. To minimize iterative calculations, the ash disposal system is charged with purchased electricity instead of derating the utility plant.

TABLE 6. PROJECTED 1984 UNIT COSTS FOR RAW MATERIALS, LABOR, AND UTILITIES

	$/unit
Process reagents	
Limestone	8.50/ton
Lime	75.00/ton
Soda ash	160.00/ton
Sulfuric acid	65.00/ton
Labor	
Operating labor	15.00/man-hr
Analyses	21.00/man-hr
Utilities	
Water	0.014/kgal
Electricity	0.037/kWh
Diesel fuel	1.20/gal

Maintenance costs are estimated as a percentage of the direct investment, based on type of equipment or facility. For process equipment maintenance costs are 8%. Pipeline maintenance is 5%. Pond maintenance is 2%, landfill maintenance is 3%, and mobile equipment maintenance is 10%.

Hourly fuel consumption is based on the equipment manufacturer's specifications. For ash trucks 5 gal/hr is used. For dozers, front loaders, and compactors 2.9, 5.0 and 5.5, and 3.0 gal/hr, respectively, are used. Total fuel consumption is based on the hourly rates and the operating hours of the disposal site.

Indirect Costs--

Plant and administrative overhead is 60% of conversion costs less utilities.

The capital structure and cost of capital for the electric utility company is assumed to be:

	Capital structure, %	Cost of capital, %
Common stock	35	11.4
Preferred stock	15	10.0
Long-term debt	50	9.0

The weighted cost of capital, based on this capital structure, is 10.0%. Depreciation for a 30-year economic life and a 30-year tax life for the utility plant is expressed as a sinking fund factor. Salvage value is assumed equal to removal costs. The annual sinking fund factor for a 30-year economic life (n_B) and 10.0% weighted cost of capital (WCC) is:

$$\text{Sinking fund factor} = \frac{\text{WCC}}{(1 + \text{WCC})^{n_B} - 1} = 0.61\%$$

The use of the sinking fund factor does not suggest that regulated utilities commonly use sinking fund depreciation. The sinking fund factor is used because it is equivalent to straight-line depreciation levelized for the economic life of the facility using the weighted cost of capital.

The levelized capital recovery factor is the weighted cost of capital plus the sinking fund factor for depreciation.

An annual interim replacement allowance of 0.56% is also included as an adjustment to the depreciation account to ensure that the initial investment will be recovered within the actual rather than the forecasted life of the facility. Since power plant retirements occur at different ages, an average service life is estimated. Many different retirement dispersion patterns occur. The type S-1 Iowa State Retirement Dispersion pattern is used (91). This S-1 pattern is symmetrical with respect to the average-life axis and the retirements are represented to occur at a low rate over many years. The interim replacement allowance does not cover replacement of individual items of equipment since these are covered by the maintenance charge.

Insurance and property taxes are assumed to be 2.50%.

The levelized income tax is calculated as follows:

$$\text{Levelized income tax} = [CRF_B + AIR\text{-}SLD]\,[1 - \frac{\text{Debt ratio x debt cost}}{WCC}]\,[\frac{ITR}{1 - ITR}]$$

where: CRF_B = Capital recovery factor
AIR = Allowance for interim replacement
SLD = Straight-line depreciation
ITR = Income tax rate
All terms are as decimal fractions

Using a 10.61% capital recovery factor (weighted cost of capital plus sinking fund factor), 0.56% allowance for interim replacements, 3.3% straight-line depreciation, 50% debt ratio, 9.0% debt cost, and a 50% income tax rate, the levelized income tax rate is 4.31%.

The levelized investment tax credit is calculated as follows:

$$\text{Levelized investment tax credit} = \frac{(CRF_B)\ (\text{Investment tax credit rate})}{(1 + WCC)\ (1 - ITR)}$$

where CRF_B, WCC, and ITR are the factors previously defined.

Using a 10.0% weighted cost of capital, 0.61% sinking fund factor, 10% investment tax credit rate, 50% income tax rate, the annual levelized investment tax credit is 1.92%.

For the accelerated tax depreciation credit, the sum of the years digits method of accelerated depreciation is used for tax purposes. On a levelized basis (using flow-through accounting) this results in a credit in the fixed charge rate as follows:

$$\text{Accelerated tax depreciation} = \frac{2CRF_B\ (n_T - \frac{1}{CRF_T})}{n_T\ (n_T + 1)\ (WCC)}$$

where: CRF_B = Capital recovery factor (weighted cost of capital plus sinking fund factor) for the economic life (as a decimal fraction)
CRF_T = Capital recovery factor for the tax life (as a decimal fraction)
n_T = Tax life (in years)

$$\text{Levelized accelerated depreciation credit} = (ATD - SLD) \times \frac{ITR}{1 - ITR}$$

where: ATD = Accelerated tax depreciation (as a decimal fraction)
SLD = Straight-line depreciation (as a decimal fraction)
ITR = Income tax rate (as a decimal fraction)

For a 50% tax rate, 30-year tax and book life, 10.0% weighted cost of capital, and 0.61% sinking fund factor, the annual levelized accelerated depreciation credit is 1.36%.

The annual levelized capital charge consisting of all of the above factors is shown below:

	Capital charge, %
Capital recovery factor	10.61
Interim replacements	0.56
Insurance and property taxes	2.50
Levelized Federal and State income tax	4.31
Investment tax credit	(1.92)
Accelerated depreciation tax credit	(1.36)
Total	14.70

The annual capital charge is applied to the total capital investment. It is recognized that land and working capital (except spare parts) are not depreciable and that provisions must be made at the end of the economic life of the facility to recover their capital value. In addition, investment credit and accelerated depreciation credit cannot be taken for land and working capital (except spare parts). The effect of these factors makes an insignificant change in the annual capital charge rate and it is therefore ignored.

SYSTEMS ESTIMATED

The ash disposal methods evaluated in this study consist of five base case processes representing major utility ash disposal practices. They are based on the 500-MW dry bottom power unit described in the premises. Four of the base cases are for the use of low-calcium 15.1% ash, 3.5% (dry basis) sulfur eastern coal in which 49,630 lb/hr of combined economizer, air heater, and ESP ash and 12,480 lb/hr of bottom ash are produced. The fly ash is assumed to be nonhardening when wet. These four cases consist of (1) direct sluicing of fly ash and bottom ash to separate ponds without water reuse (once-through transportation water), (2) the same system with recycled transportation water, (3) direct sluicing of fly ash and bottom ash to temporary ponds, followed by excavation and trucking of both to a common landfill, and (4) collection of dry fly ash in silos and bottom ash in dewatering bins from which they are trucked moist to separate landfills.

The fifth base case represents a situation in which the power plant is burning a western-type coal that contains about 1% calcium, making the fly ash subject to spontaneous cementitious reactions when wet. The handling and disposal system is designed to forestall these self-hardening reactions by keeping the fly ash dry until it is placed in the disposal site. The coal in this case contains 9.7% ash, producing 37,890 lb/hr of combined economizer, air heater, and ESP ash and 9,550 lb/hr of bottom ash.

All of the systems are sized for intermittent removal of ash from the collection hoppers. For the economizer, air-heater, and ESP fly ash system the operating time is 12 hours in 24 hours. For the bottom ash system the operating time is 6 hours in 24 hours. All flow rates in the material balances are expressed as 24-hour averages, however. Intermittent flow rates in the material balance are identified by footnote.

BASE CASE 1 - DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

This case consists of the simplest, and historically the most widely used, ash disposal method. Water from any convenient large-volume source (such as from once-through cooling water or directly from the power-plant water intakes) is used to sluice both fly ash and bottom ash to disposal ponds. The transportation water flows from the ponds, is treated to meet NPDES pH requirements, and returns to the body of natural water from which it came. In this case a river is assumed to be the water body. The flow diagram, disposal site plan, and plot plan are shown in Figures 7, 8, and 9. The material balance and equipment list are shown in Tables 7 and 8.

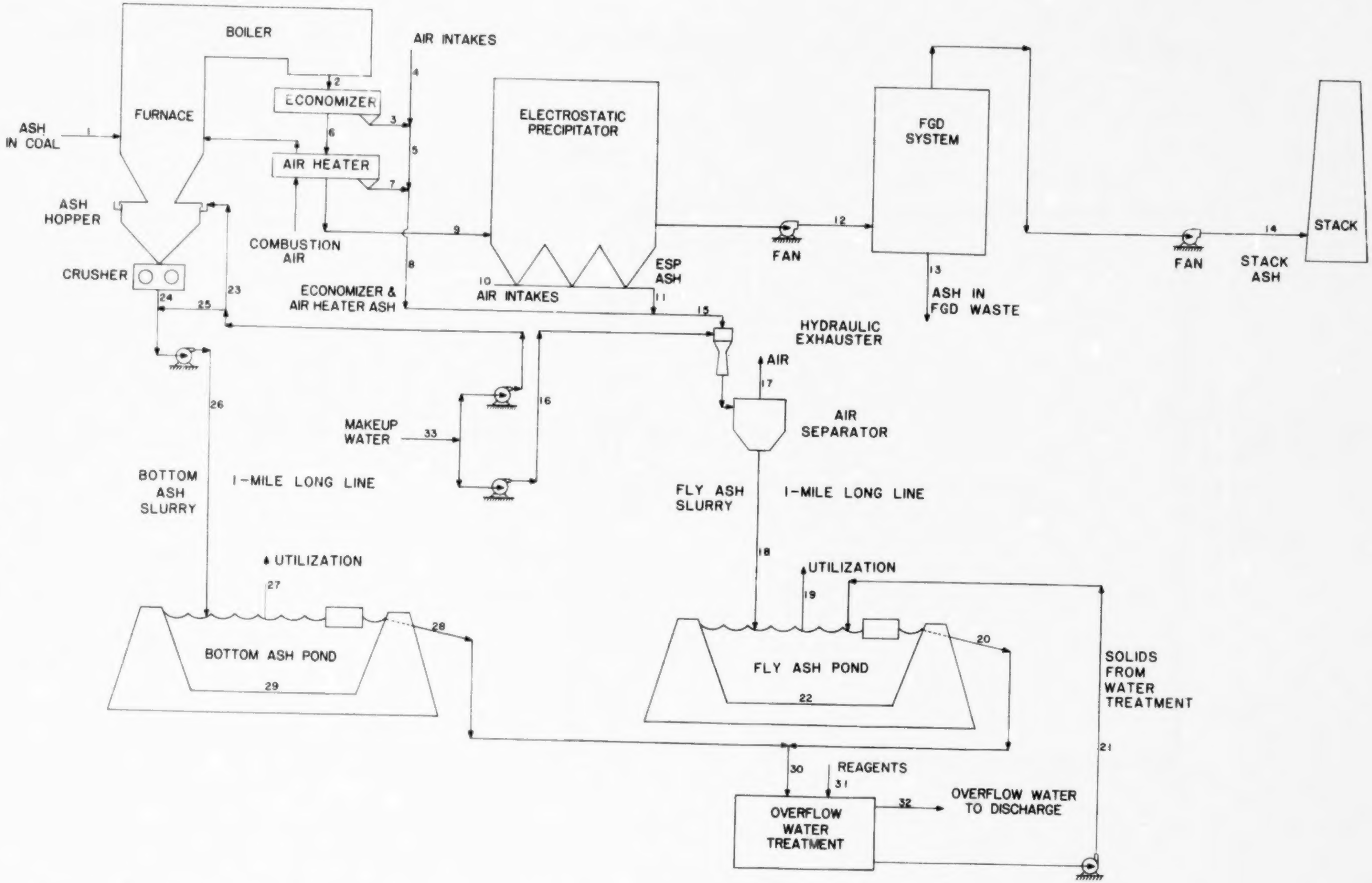
BOILER
FURNACE
ASH IN COAL
1
2
ECONOMIZER
3
6
AIR HEATER
7
AIR INTAKES
4
5
8
9
ASH HOPPER
COMBUSTION AIR
CRUSHER
24
25
23
ECONOMIZER & AIR HEATER ASH
ELECTROSTATIC PRECIPITATOR
10
AIR INTAKES
ESP ASH
11
15
FAN
12
FGD SYSTEM
13
ASH IN FGD WASTE
FAN
14
STACK
STACK ASH
HYDRAULIC EXHAUSTER
AIR
17
AIR SEPARATOR
16
MAKEUP WATER
33
26
BOTTOM ASH SLURRY
I-MILE LONG LINE
FLY ASH SLURRY
I-MILE LONG LINE
18
UTILIZATION
27
BOTTOM ASH POND
29
28
UTILIZATION
19
FLY ASH POND
22
20
SOLIDS FROM WATER TREATMENT
21
30
REAGENTS
31
OVERFLOW WATER TREATMENT
32
OVERFLOW WATER TO DISCHARGE

Figure 7. Flow diagram. Base case 1, direct ponding of nonhardening ash without water reuse.

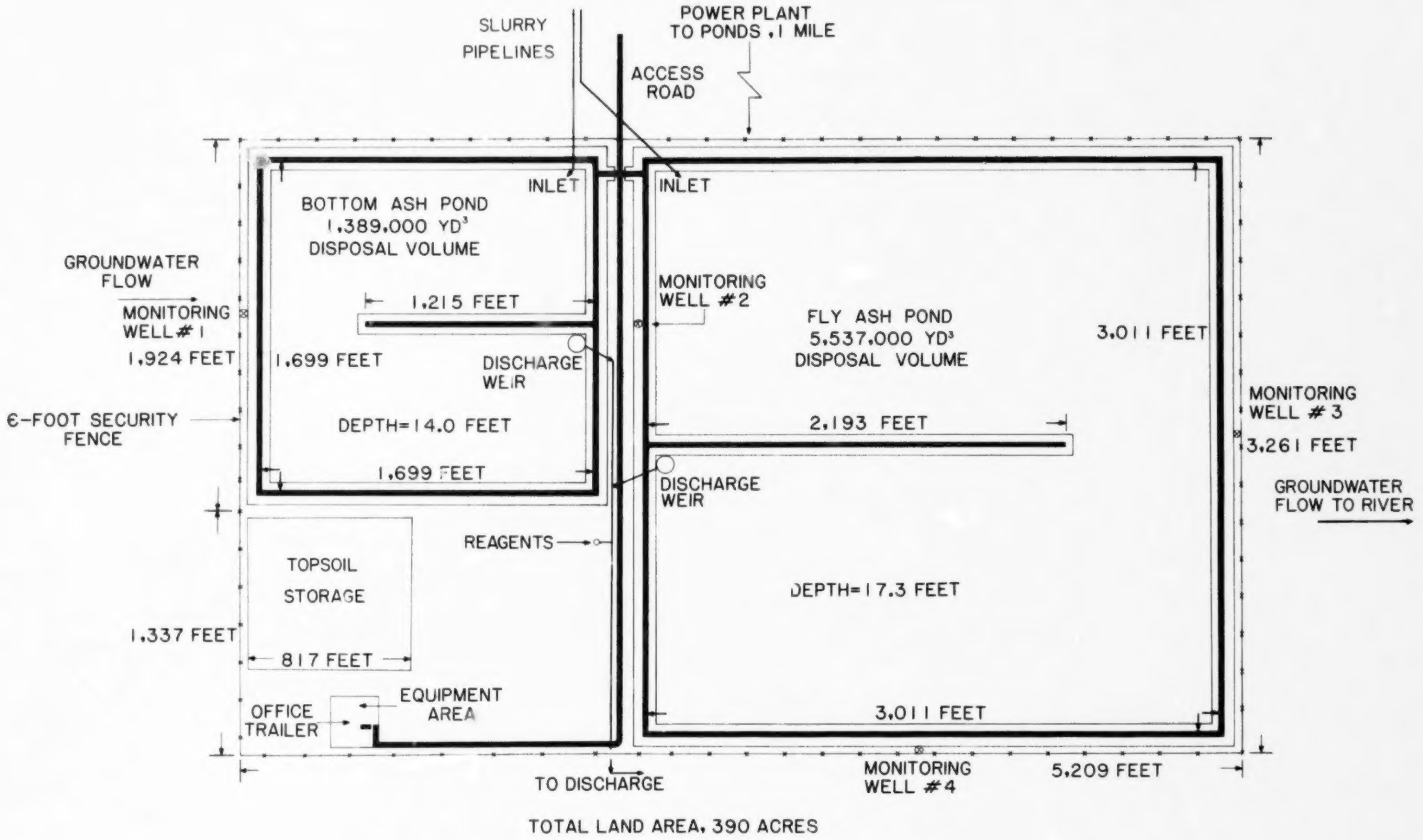
SLURRY
PIPELINES
POWER PLANT
TO PONDS .1 MILE
ACCESS
ROAD
INLET
INLET
BOTTOM ASH POND
1,389,000 YD³
DISPOSAL VOLUME
GROUNDWATER
FLOW
MONITORING
WELL #1
1,924 FEET
1,215 FEET
1,699 FEET
DISCHARGE
WEIR
6-FOOT SECURITY
FENCE
DEPTH=14.0 FEET
1,699 FEET
MONITORING
WELL #2
FLY ASH POND
5,537,000 YD³
DISPOSAL VOLUME
3,011 FEET
MONITORING
WELL #3
3,261 FEET
2,193 FEET
DISCHARGE
WEIR
GROUNDWATER
FLOW TO RIVER
REAGENTS
TOPSOIL
STORAGE
DEPTH=17.3 FEET
1,337 FEET
817 FEET
OFFICE
TRAILER
EQUIPMENT
AREA
3,011 FEET
TO DISCHARGE
MONITORING
WELL #4
5,209 FEET
TOTAL LAND AREA, 390 ACRES

Figure 8. Disposal site. Base case 1, direct ponding of nonhardening ash without water reuse.

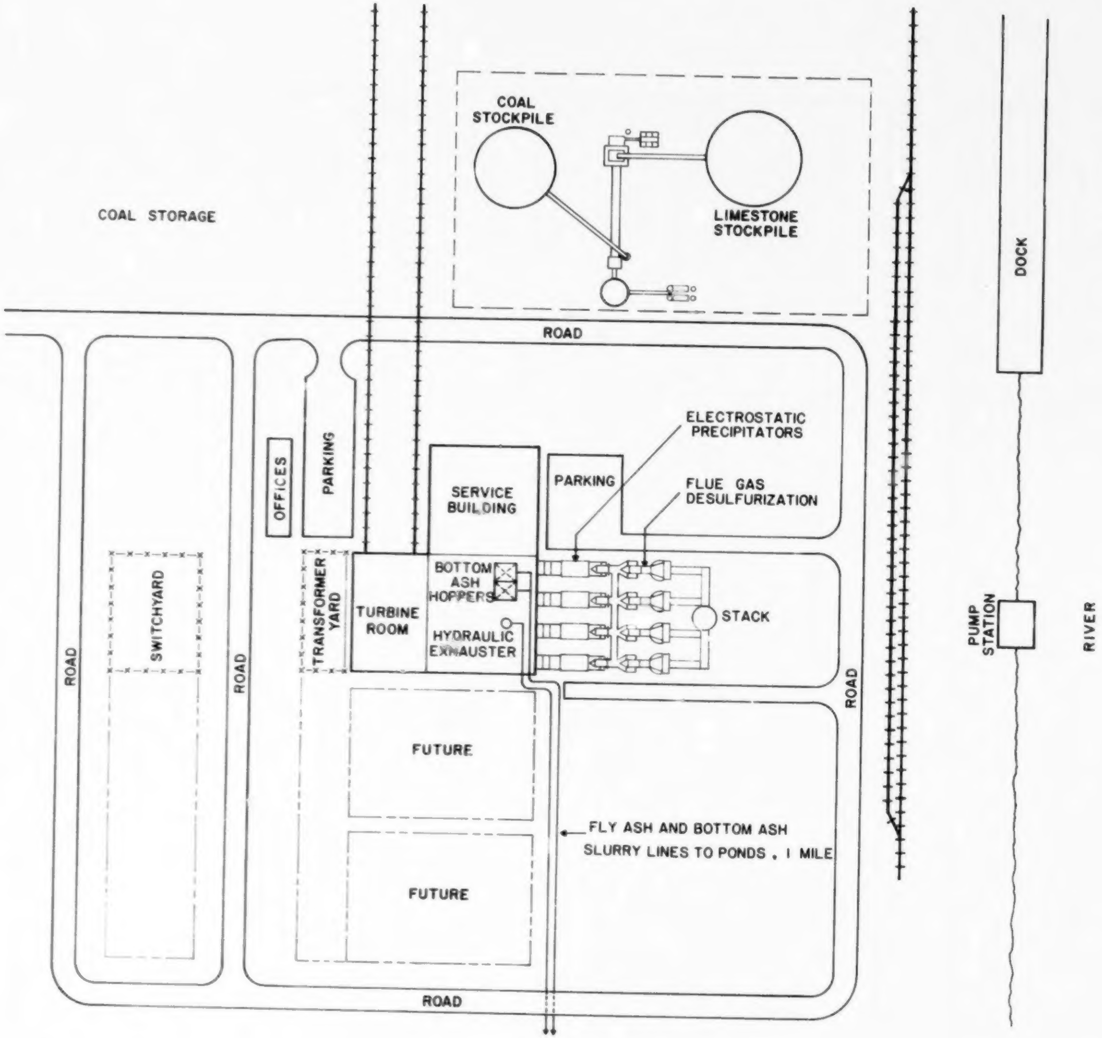
COAL STORAGE
COAL STOCKPILE
LIMESTONE STOCKPILE
DOCK
ROAD
PARKING
OFFICES
SERVICE BUILDING
PARKING
ELECTROSTATIC PRECIPITATORS
FLUE GAS DESULFURIZATION
SWITCHYARD
TRANSFORMER YARD
TURBINE ROOM
BOTTOM ASH HOPPERS
HYDRAULIC EXHAUSTER
STACK
PUMP STATION
RIVER
ROAD
ROAD
ROAD
FUTURE
FUTURE
FLY ASH AND BOTTOM ASH SLURRY LINES TO PONDS, 1 MILE
ROAD

Figure 9. Plot plan. Base case 1, direct ponding of nonhardening ash without water reuse.

TABLE 7. MATERIAL BALANCE

BASE CASE 1 - DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Stream No.	1	2	3	4	5
	Description	Coal ash to furnace	Ash to economizer	Ash collected from economizer	Air intake to economizer ash pneumatic system	Economizer ash in pneumatic system
1	Total stream, lb/hr	62,400	49,920	1,560	100	1,660
2						
3	Stream components, lb/hr					
4	Ash	62,400	49,920	1,560		1,560
5	Water					
6	Air				100	100
7						
8	Ft^3/min, 60°F				22	
9	Gal/min					
10	Percent solids					

	Stream No.	6	7	8	9	10
	Description	Ash to air heater	Ash collected from air heater	Economizer-air heater ash in pneumatic system	Ash to ESP	Air intake to ESP ash pneumatic system
1	Total stream, lb/hr	48,360	1,560	3,220	46,800	1,390
2						
3	Stream components, lb/hr					
4	Ash	48,360	1,560	3,120	46,800	
5	Water					
6	Air			100		1,390
7						
8	Ft^3/min, 60°F					303
9	Gal/min					
10	Percent solids					

	Stream No.	11	12	13	14	15
	Description	ESP ash in pneumatic system	Ash to FGD system	Ash in FGD waste	Ash to stack	Ash to hydraulic exhauster
1	Total stream, lb/hr	47,900	285	143	142	51,120
2						
3	Stream components, lb/hr					
4	Ash	46,510	285	143	142	49,630
5	Water					
6	Air	1,390				1,490
7						
8	Ft^3/min, 60°F					
9	Gal/min					
10	Percent Solids					

	Stream No.	16	17	18	19	20
	Description	Water to hydraulic exhauster[a]	Exhaust air from hydraulic exhauster[a]	Fly ash slurry from hydraulic exhauster[a]	Fly ash utilization	Overflow water from fly ash pond[a]
1	Total stream, lb/hr	595,600	1,490	645,230	0	553,630
2						
3	Stream components, lb/hr					
4	Ash			49,630		500
5	Water	595,600		595,600		553,130
6	Air		1,490			
7						
8	Ft^3/min, 60°F		325			
9	Gal/min	1,190		1,241		1,106
10	Percent solids			7.7		

(continued)

TABLE 7 (continued)

	Stream No.	21	22	23	24	25
	Description	Solids from overflow water treatment[a,b]	Settled fly ash in pond[a]	Water to bottom ash hopper[b]	Slurry from bottom ash crusher[b]	Water to bottom ash slurry[b]
1	Total stream, lb/hr	2,280	93,880	50,900	63,380	98,800
2						
3	Stream components, lb/hr					
4	Ash	570	49,700		12,480	
5	Water	1,710	44,180	50,900	50,900	98,800
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min	4		102	114	198
10	Percent solids	25	53		20	

	Stream No.	26	27	28	29	30
	Description	Bottom ash slurry from pump[b]	Bottom ash utilization	Overflow water from bottom ash pond[b]	Settled bottom ash in pond[b]	Overflow water to treatment[a,b]
1	Total stream, lb/hr	162,180	0	138,830	23,350	692,460
2						
3	Stream components, lb/hr					
4	Ash	12,480		120	12,360	620
5	Water	149,700		138,710	10,990	691,840
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min	312		278		1,384
10	Percent solids	7.7			53	

	Stream No.	31	32	33		
	Description	Reagents	Overflow water to discharge[a,b]	Makeup water[a,b]		
1	Total stream, lb/hr	20	690,200	745,320		
2						
3	Stream components, lb/hr					
4	Ash		50			
5	Water		690,150	745,320		
6	Air					
7	H_2SO_4	20				
8	Ft^3/min, 60°F					
9	Gal/min	0.02	1,380	1,490		
10	Percent solids					

a. 24-hour average based on 12 hr/day operation for fly ash transport.
b. 24-hour average based on 6 hr/day operation for bottom ash transport.

TABLE 8. EQUIPMENT LIST, DESCRIPTION, AND MATERIAL COST

BASE CASE 1 - DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

Item (number): description	Material cost, delivered, 1982 k$
Area 1--Fly Ash Collection and Transfer	
1. Economizer ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 15 ft wide x 16 ft deep, thermally isolated design, constructed of 1/2-in. carbon steel	27
2. Air heater ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 7 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, insulated	21
3. ESP ash hoppers (32): Inverted pyramid-type hopper, 18 ft long x 12 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, heat traced and insulated	373
4. Package-unit fly ash collecting and conveying system comprising (1):	228
a. Vacuum pneumatic conveying lines for economizer-air heater ash and ESP ash (2): Pipelines and pipe fittings for vacuum pneumatic conveyance of fly ash, 25 ton/hr conveying capacity with 600-ft equivalent length system, 6-in. I.D. branch lines and 8-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard® or equivalent pipe fittings	
b. Fly ash and air inlet valves (40): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 6-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	
c. Line segregating valves (10): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 6-in. I.D. port, cast iron body, stainless steel slide gate	
d. Vacuum breaker valves (2): Vacuum breaker valve for control of vacuum in main conveying line to hydraulic exhauster, 8-in. I.D. port, cast iron body	

(continued)

TABLE 8 (continued)

Item (number): description	Material cost, delivered, 1982 k$
e. Hydraulic exhausters for vacuum pneumatic conveying system (2): Vacuum producing hydraulic exhauster with 8-in. I.D. air-ash inlet, 8-in. I.D. water connection, and 10-in. I.D. discharge, cast iron body with 250 psi water ejector head, chromium-iron alloy air-ash inlet liner, stainless steel water nozzle tips, ceramic-lined venturi throat; vertical installation, tapped for vacuum and pressure gauges	
f. System control unit (2): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and water to the hydraulic exhauster; includes gauges for manual reading and override switches for manual operation	
5. Water supply pumps for hydraulic exhausters (4 + 1 spare): Centrifugal pump, 600 gpm, 480-ft head, carbon steel body exhausters and impeller; 125 hp (costed 75% in Area 1 and 25% in Area 2)	57
Total, Area 1	706
Area 2--Fly Ash Conveyance to Disposal Site	
1. Water supply pumps for fly ash conveyance (4 + 1 spare): Same pumps as in Area 1, Item 5 (costed 25% in Area 2 and 75% conveyance in Area 1)	19
2. Air separator (1): Baffle-type cylindrical air separator tank with cone bottom, dual 8-in. I.D. inlets and single 12-in. I.D. slurry outlet, 8-ft I.D. carbon steel shell with 30-mm basalt lining	25
3. One-mile slurry pipeline to pond (1 + 1 spare): Pipeline comprising 132 40-ft-long sections of flanged steel pond pipe, 12-in. I.D., schedule 80 carbon steel and six elbows or bends, 12-in. I.D. schedule 80 I.D. hardened steel	(366)a
Total, Area 2	44

(continued)

TABLE 8 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 3--Fly Ash Disposal Site	
1. Fly ash pond (1): Pond, 3,011 ft square x 17.3 ft deep, 1-ft-thick clay liner, earthen perimeter dikes and 2,193-ft-long divider dike graded on top for use as service roads, pond area of 244 acres, pond volume of 5,537,000 yd^3, topsoil storage of 12.2 acres contiguous with topsoil storage for adjacent bottom ash pond, office trailer and equipment storage area common for fly ash and adjacent bottom ash pond, pond periphery monitored by three monitoring wells, fly ash pond isolated by 6-ft-high security fence which surrounds entire disposal site	(8,509)a
Total, Area 3	0
Area 4--Fly Ash Water Treatment and Recycle of Water (Costed 80% in Area 4 and 20% in Area 8)	
1. Sulfuric acid storage tank for pH control of water to discharge (1): Cylindrical steel tank 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2
2. Metering pump for sulfuric acid (1 + 1 spare): Positive displacement metering pump 0.01 to 1 gpm, 0 psig, Carpenter 20® alloy or similar corrosion resistance to 93% sulfuric acid; 0.25 hp, flow rate controlled by a pH controller	2
3. Agitator for mixing of treated water (1): Agitator with 24-in.-diameter nickel-chromium blade; 5 hp	3
4. Pump for solids slurry from water treatment (1 + 1 spare): Centrifugal pump, 5 gpm, 20 psig, carbon steel body and impeller, 0.25 hp	1
5. Automatic sampler for water to discharge (1): Automatic sampler with sample size controlled by flow rate, refrigerated storage of composite sample; all-weather housing	4
Total, Area 4	12

(continued)

TABLE 8 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 5--Bottom Ash Collection and Transfer	
1. Water supply pumps for bottom ash hopper and slurry (2 + 1 spare): Centrifugal pump, 600 gpm, 250-ft head, carbon steel body hopper and slurry and impeller, 75 hp	34
2. Bottom ash hopper assembly (1): Double-V hopper with 3,320 ft^3 capacity for 12-hr ash containment, supported independently of furnace-boiler and mated to furnace through a water seal trough spanning the furnace seal plate, hopper body of 3/8-in.-thick carbon steel plate, hopper lined with monolithic refractory 9 in. thick in upper section and 6 in. thick in lower section, stainless steel seal trough and overflow weirs, assembly includes poke doors, lighted observation windows, access doors, and hydraulically operated ash exit doors; each V-section of hopper includes two hopper-type, double-roll grinders with cast iron body and 10-in.-diameter x 2-ft-long manganese steel rolls; 60 hp	352
Total, Area 5	386
Area 6--Bottom Ash Conveyance to Disposal Site	
1. Slurry pumps for pipeline conveyance (1 + 1 spare): Centrifugal slurry pump, 1,440 gpm, 350-ft head, Ni-Hard liner and impeller, 250-hp motor	57
2. Shutoff and crossover valves (10): Air-operated gate valve, 8-in. I.D. port, Ni-Hard	23
3. One-mile basalt-lined slurry pipeline to pond, normal use (1): Pipeline comprising 294 18-ft-long sections of flanged, basalt-lined steel pipe, 8 in. I.D. and six basalt-lined elbows or bends, 8 in. I.D.	(373)[a]
4. Spare slurry pipeline to pond (1): Pipeline comprising 132 40-ft-long sections of flanged steel pipe, 8 in. I.D., schedule 80, carbon steel and six hardened steel elbows or bends, 8 in. I.D.	(93)[a]

(continued)

TABLE 8 (continued)

Item (number): description	Material cost, delivered, 1982 k$
5. Pipeline agitators (2): Agitator with single horizontal tooth roll, cast iron body, manganese steel roll and wear plate; 25 hp	30
Total, Area 6	110
Area 7--Bottom Ash Disposal Site	
1. Bottom ash pond (1): Pond, 1,699 ft square x 14.0 ft deep, with 1-ft-thick clay liner, earthen perimeter dikes and 1,215-ft-long divider dike graded on top for use as service roads, pond area of 85 acres, pond volume of 1,389,000 yd^3, topsoil storage of 3.1 acres contiguous with topsoil storage for adjacent fly ash pond, office trailer and equipment storage are common for bottom ash and adjacent fly ash pond, pond periphery monitored by two monitoring wells, bottom ash pond isolated by 6-ft-high security fence which surrounds entire disposal site	(2,127)[a]
Total, Area 7	0
Area 8--Bottom Ash Water Treatment and Recycle of Water (Costed 20% in Area 8 and 80% in Area 4	
1. Sulfuric acid storage tank for pH control of water to discharge (1): Same tank as in Area 4, Item 1	0.5
2. Metering pump for sulfuric acid (1): Same pump as in Area 4, Item 2	0.5
3. Agitator for mixing of treated water (1): Same agitator as in Area 4, Item 3	0.75
4. Pump for solids slurry from water treatment (1 + 1 spare): Same pump as in Area 4, Item 4	0.25
5. Automatic sampler for water to discharge (1): Same sampler as in Area 4, Item 5	1
Total, Area 8	3
Total, Base Case 1	1,261

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a. Costs shown in parentheses are informational and are not included in area or base case totals for equipment material costs.

Fly Ash Collection

Economizer, air heater, and ESP ash are collected in hoppers beneath the units. The ash is removed intermittently by a vacuum pneumatic conveying system with hydraulic exhausters. The ash-air-water mixture from the exhausters is discharged into an air separator from which the ash-water suspension flows by gravity through a transport line to the ash pond.

The ash hoppers have a 12-hour-capacity and are constructed of plate steel in the form of an inverted pyramid. An ash valve at the bottom connects to the ash conveying system. Four hoppers each are used for the economizer and air heater ash and 32 hoppers are used for the ESP ash. The air heater and ESP hoppers connect directly to the bottom of the units. The economizer hoppers are thermally isolated from the economizer flue gas by a throat and chute to prevent sintering of the ash. The air heater and ESP hoppers are insulated to maintain the interior temperature above the sulfuric acid and water saturation temperatures of the flue gas. The ESP hoppers are also electrically heated for the same reason. Condensation in the hoppers can cause caking or freezing that hinders ash removal.

Two hydraulic exhausters are used. Each is supplied with 1,190 gpm of water at 250 psig by 2 centrifugal pumps. The exhausters consist of cast iron frames with 8-inch-diameter air inlets and 10-inch-diameter outlets. The water is ejected through annular nozzles above a basalt-lined venturi throat, producing a design vacuum of 19 in. Hg at the air inlet.

The ash vacuum pneumatic conveying system consists of two 8-inch-diameter main lines and 6-inch-diameter secondary lines to the ash and inlet air valves on the ash hoppers. Each main line is connected to half of the ash hoppers. Both of the main lines can be valved to either ejector so that ash can be removed from all hoppers by either ejector. Vacuum breakers on the main lines prevent backflow during shutdowns.

The system is designed for operation at 50 tons/hr, twice the maximum ash production rate, with both ejectors operating. In normal operation both ejectors are operated about one-half of the time. The hoppers are emptied sequentially by a programmed control system. Segregation valves on the secondary lines isolate inactive lines. The ash flow rate from the hoppers is controlled by the ash valve which admits controlled quantities of air and ash to the conveying line. The ash rate is automatically controlled to maintain a preset vacuum level at the valve, thus ensuring the most efficient ash-to-air ratio and air velocity. The valve is automatically closed when a large decrease in vacuum indicates an empty hopper and the system is automatically shifted to the next hopper in the sequence. The system is designed for a maximum equivalent conveying length of 600 feet. The design velocity is about 1,800 ft/min with a 19 in. Hg vacuum at the ejector. All piping and fittings are of abrasion-resistant materials.

The hydraulic exhausters are mounted just above a baffle-type air separator tank and the ash-air-water mixture from the exhausters is injected into opposite sides of the tank. The air separated from the mixture is vented to the atmosphere and the ash-water slurry, composed of 7.7% solids, flows by gravity into the slurry pipeline to the ash pond. The ejectors and separator are mounted in the power-plant building structure to provide an 80-foot gravity head at the separator tank outlet.

Bottom Ash Collection

Bottom ash is collected in a standard design double-vee-bottom steel hopper with a 12-hour capacity. The hopper has a continuously sluiced refractory lining and is connected to the boiler with a trough and plate water seal to permit independent expansion and contraction. Each vee section feeds a double-roll 10-inch-diameter by 2-foot-long clinker grinder. The clinker grinders are connected to two 1,440 gpm ash transport pumps, one of which is a spare. The pumps are connected to the primary and spare bottom ash pipelines with manifolds to permit the use of either pump and either pipeline. Water for the boiler-hopper seal, lining sluices, ash hopper sluices, and ash transportation is provided by two 600 gpm centrifugal pumps fed by condenser water or directly from the river water intake.

The system is designed to operate at about four times the bottom ash production rate, permitting intermittent operation of about 2 hours per shift when trouble free. When the ash hopper is to be emptied the feed door to the clinker grinder is opened and the ash is sluiced through the clinker grinders with water jets situated around the walls of the hopper. The water-to-ash ratio of the slurry leaving the clinker grinder is about 5 to 1 by weight. This slurry is drawn into the ash transport pump along with sufficient additional water to reduce the slurry solids to 7.7%. The diluted slurry is pumped into the transport line at an instantaneous rate of about 1,250 gpm.

Ash Transportation

Fly ash and bottom ash are transported one mile to the disposal ponds in separate pipelines supported on concrete piers. The fly ash pipeline consists of a 12-inch-diameter, flanged, schedule 80 carbon steel pipe on concrete piers. The heavy schedule and hardened steel fittings are used to provide a longer wear life. An identical spare line is provided.

The primary bottom ash pipeline consists of an 8-inch-diameter, flanged, basalt-lined steel pipe on concrete piers. An 8-inch-diameter, schedule 80 carbon steel unlined spare with hardened steel fittings is also provided. An intermediate agitator is situated in each bottom ash pipeline to reduce settling.

Ash Ponds

The fly ash and bottom ash pipelines discharge into separate contiguous earthern-diked square ponds constructed as described in the premises. Both ponds are sized for the life of the power plant using a 55 lb/ft^3 dry bulk density for both ashes. The fly ash pond is about 3,000 feet square from dike crest to dike crest, occupies about 200 contained acres, has a 5.5 million yd^3 disposal volume, and is designed for a 17-foot ash depth when full. The bottom ash pond is about 1,700 feet square from crest to crest, occupies about 60 acres, has a 1.4 million yd^3 disposal volume, and is designed for a 14-foot ash depth when full.

The total disposal area occupies 390 acres. In addition to the area occupied by the dikes, this includes the perimeter, topsoil storage, an office and equipment area, and roadways. The entire disposal area is fenced and it is provided with electricity, water, and sewer facilities. Four ground water monitoring wells are also provided.

The ash slurries are discharged onto riprap at a corner of their respective ponds on the side closed by the diverter dike. Overflow intakes are situated on the opposite side of the diverter dike. The slurry is thus forced to flow around the diverter dike to reach the water outlet, allowing increased area, reduced velocity, and time for the ash to settle. The overflow intakes are surrounded by floating skimmer weirs to prevent floating ash from entering the intakes.

The overflows from both ponds discharge through pipes into a single rock-lined outflow channel that returns the water to the river. A section of concrete channel is provided for additional skimmers, pH monitoring, and a Parshall flume for flow rate monitoring. The pH is adjusted automatically, if above 9, by addition of sulfuric acid. Periodically, solids are manually removed from the channel, reslurried, and pumped back to the fly ash pond.

The 24-hour average flow rate of fly ash slurry entering the fly ash pond is 1,200 gal/min and the maximum instantaneous rate is 2,500 gal/min. The 24-hour average flow rate through the overflow is 1,100 gal/min. The 24-hour average flow rate of bottom ash slurry entering the bottom ash pond is about 300 gal/min and the maximum instantaneous rate is about 1,200 gal/min. The 24-hour average flow rate through the overflow is about 280 gal/min. The combined overflow streams have a 24-hour average flow rate of about 1,400 gal/min. The pond filling rates, based on the 55 lb/ft3 dry bulk density, are 800 yd^3/day for fly ash and 200 yd^3/day for bottom ash.

BASE CASE 2 - DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

This case is essentially the same as base case 1 except that the pond overflow water is recycled. The use of water recycle can represent either a limited water supply or a necessity to meet pollutant discharge limitations, although the latter is a more common application. The flow diagram, disposal site plan, and plot plan are shown in Figures 10, 11, and 12. The material balance and equipment list are shown in Tables 9 and 10.

The same fly ash and bottom ash collection, transportation, and ponding procedures are used in this base case as are used in base case 1. The base case 1 process, equipment, and pond site descriptions also apply to this base case. In this base case, however, the pond overflow is pumped back to a storage tank at the power plant for reuse as transportation water. A portion of the water returned from the ponds is treated to reduce its hardness. This, along with replacement of the water lost in the settled ash is assumed to control scaling.

The fly ash and bottom ash are collected and transported to the pond with equipment and procedures identical to those described in base case 1. The

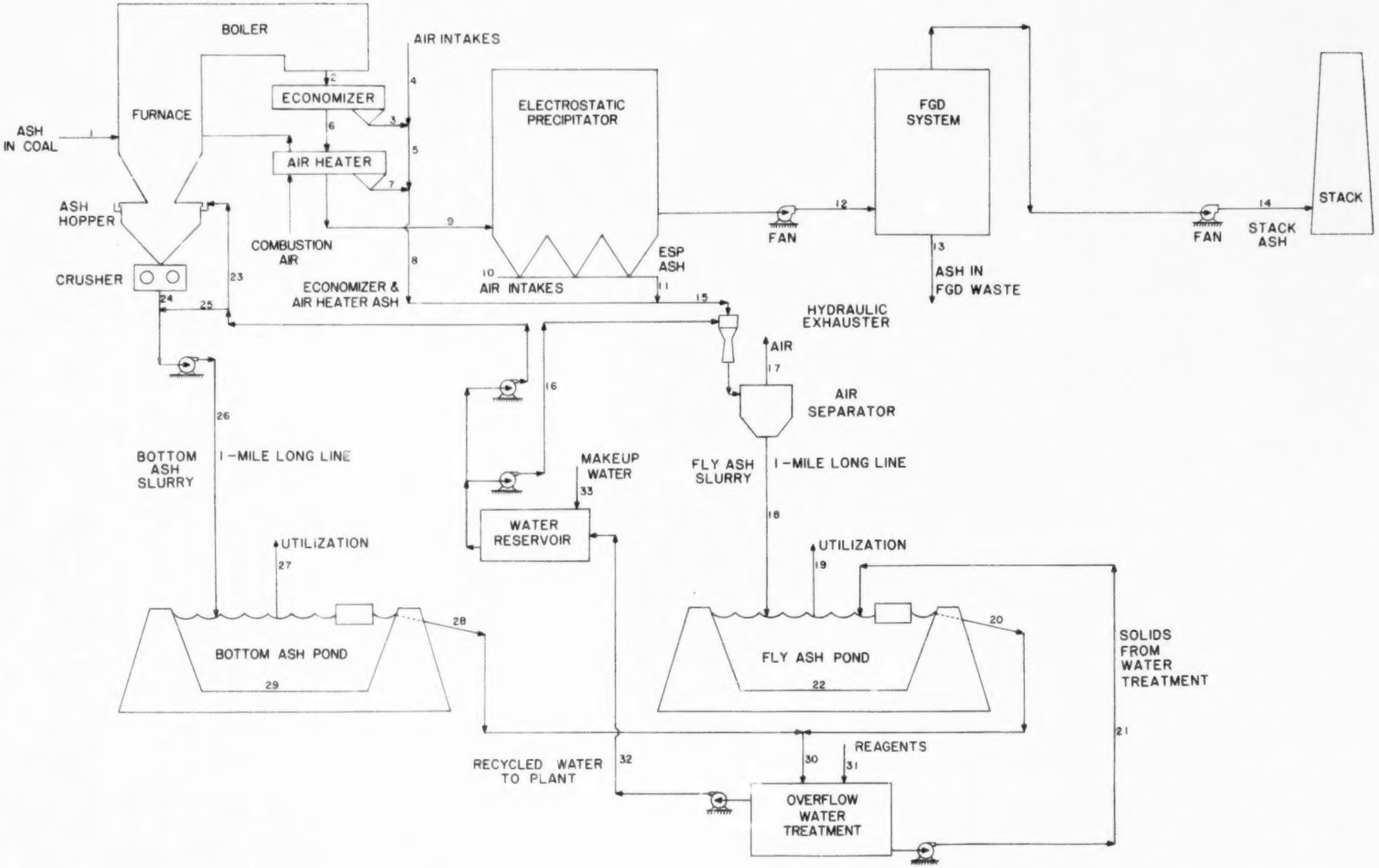

ASH IN COAL
1
BOILER
FURNACE
ASH HOPPER
CRUSHER
2
ECONOMIZER
3
6
AIR HEATER
7
COMBUSTION AIR
AIR INTAKES
4
5
8
9
ECONOMIZER & AIR HEATER ASH
ELECTROSTATIC PRECIPITATOR
10
AIR INTAKES
ESP ASH
11
15
FAN
12
FGD SYSTEM
13
ASH IN FGD WASTE
FAN
14
STACK ASH
STACK
23
24
25
26
BOTTOM ASH SLURRY
1-MILE LONG LINE
16
HYDRAULIC EXHAUSTER
AIR
17
AIR SEPARATOR
FLY ASH SLURRY
1-MILE LONG LINE
18
MAKEUP WATER
33
WATER RESERVOIR
UTILIZATION
27
BOTTOM ASH POND
28
29
UTILIZATION
19
FLY ASH POND
20
22
SOLIDS FROM WATER TREATMENT
21
RECYCLED WATER TO PLANT
32
30
REAGENTS
31
OVERFLOW WATER TREATMENT

Figure 10. Flow diagram. Base case 2, direct ponding of nonhardening ash with water reuse.

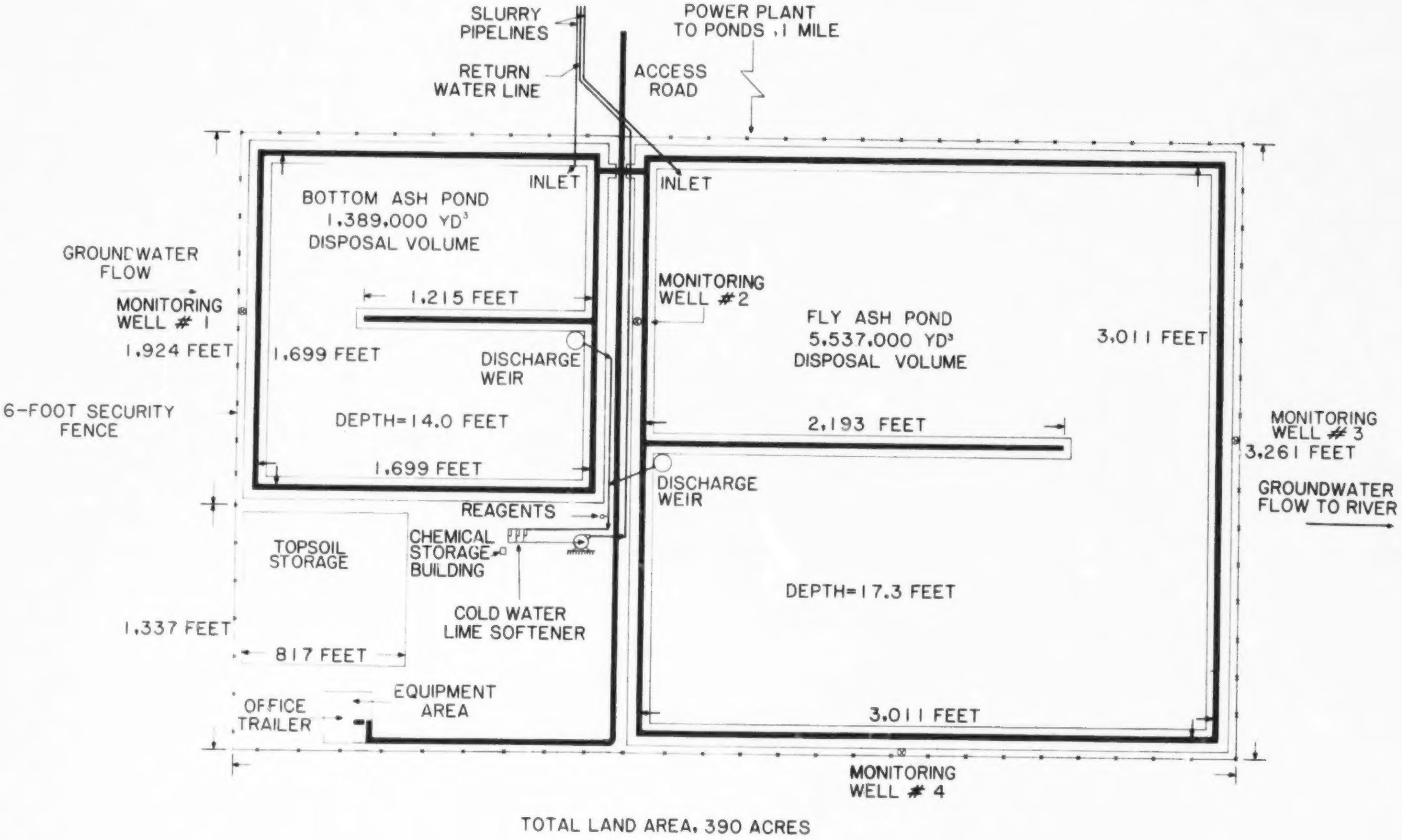

SLURRY PIPELINES
RETURN WATER LINE
ACCESS ROAD
POWER PLANT TO PONDS, 1 MILE
INLET
INLET
BOTTOM ASH POND
1,389,000 YD³
DISPOSAL VOLUME
GROUNDWATER FLOW
MONITORING WELL # 1
1,924 FEET
1,215 FEET
1,699 FEET
DISCHARGE WEIR
DEPTH=14.0 FEET
1,699 FEET
6-FOOT SECURITY FENCE
MONITORING WELL #2
FLY ASH POND
5,537,000 YD³
DISPOSAL VOLUME
3,011 FEET
2,193 FEET
DISCHARGE WEIR
MONITORING WELL # 3
3,261 FEET
GROUNDWATER FLOW TO RIVER
REAGENTS
CHEMICAL STORAGE BUILDING
TOPSOIL STORAGE
COLD WATER LIME SOFTENER
1,337 FEET
817 FEET
EQUIPMENT AREA
OFFICE TRAILER
DEPTH=17.3 FEET
3,011 FEET
MONITORING WELL # 4
TOTAL LAND AREA, 390 ACRES

Figure 11. Disposal site. Base case 2, direct ponding of nonhardening ash with water reuse.

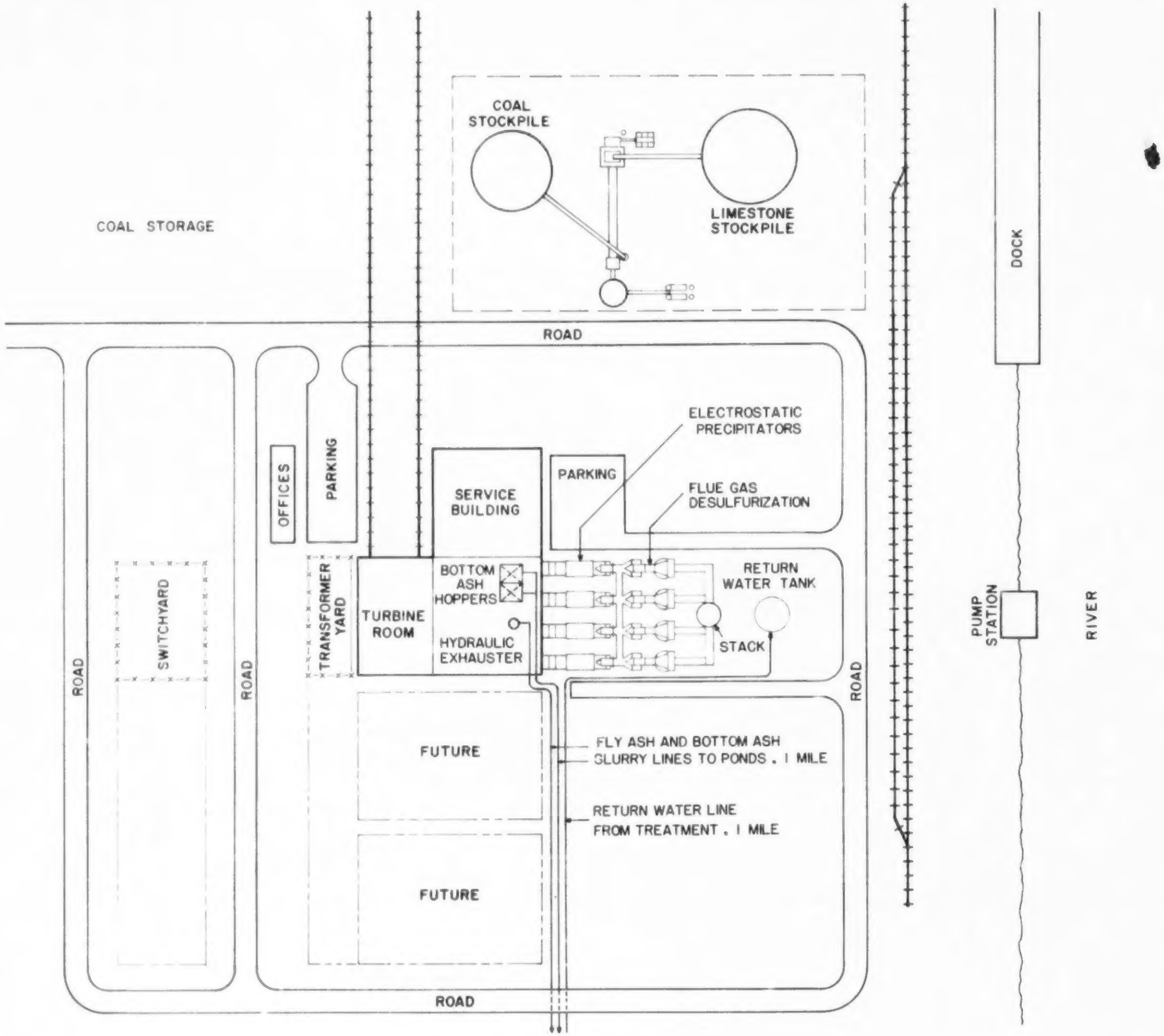

COAL STORAGE
COAL STOCKPILE
LIMESTONE STOCKPILE
DOCK
ROAD
ELECTROSTATIC PRECIPITATORS
FLUE GAS DESULFURIZATION
PARKING
SERVICE BUILDING
OFFICES
PARKING
BOTTOM ASH HOPPERS
TURBINE ROOM
HYDRAULIC EXHAUSTER
TRANSFORMER YARD
SWITCHYARD
RETURN WATER TANK
STACK
PUMP STATION
RIVER
ROAD
ROAD
ROAD
FUTURE
FUTURE
FLY ASH AND BOTTOM ASH SLURRY LINES TO PONDS . I MILE
RETURN WATER LINE FROM TREATMENT . I MILE
ROAD

Figure 12. Plot plan. Base case 2, direct ponding of nonhardening ash with water reuse.

TABLE 9. MATERIAL BALANCE

BASE CASE 2 - DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

	Stream No.	1	2	3	4	5
	Description	Coal ash to furnace	Ash to economizer	Ash collected from economizer	Air intake to economizer ash pneumatic system	Economizer ash in pneumatic system
1	Total stream, lb/hr	62,400	49,920	1,560	100	1,660
2						
3	Stream components, lb/hr					
4	Ash	62,400	49,920	1,560		1,560
5	Water					
6	Air				100	100
7						
8	Ft^3/min, 60°F				22	
9	Gal/min					
10	Percent solids					

	Stream No.	6	7	8	9	10
	Description	Ash to air heater	Ash collected from air heater	Economizer-air heater ash in pneumatic system	Ash to ESP	Air intake to ESP ash pneumatic system
1	Total stream, lb/hr	48,360	1,560	3,220	46,800	1,390
2						
3	Stream components, lb/hr					
4	Ash	48,360	1,560	3,120	46,800	
5	Water					
6	Air			100		1,390
7						
8	Ft^3/min, 60°F					303
9	Gal/min					
10	Percent solids					

	Stream No.	11	12	13	14	15
	Description	ESP ash in pneumatic system	Ash to FGD system	Ash in FGD waste	Ash to stack	Ash to hydraulic exhauster
1	Total stream, lb/hr	47,900	285	143	142	51,120
2						
3	Stream components, lb/hr					
4	Ash	46,510	285	143	142	49,630
5	Water					
6	Air	1,390				1,490
7						
8	Ft^3/min, 60°F					
9	Gal/min					
10	Percent solids					

	Stream No.	16	17	18	19	20
	Description	Water to hydraulic exhauster	Exhaust air from hydraulic exhauster	Fly ash slurry from hydraulic exhauster	Fly ash utilization	Overflow water from fly ash pond
1	Total stream, lb/hr	595,640	1,490	645,270	0	553,630
2						
3	Stream components, lb/hr					
4	Ash	40		49,630		500
5	Water	595,600		595,600		553,130
6	Air		1,490			
7						
8	Ft^3/min, 60°F		325			
9	Gal/min	1,190		1,241		1,106
10	Percent solids			7.7		

(continued)

TABLE 9 (continued)

	Stream No.	21	22	23	24	25
	Description	Solids from overflow water treatment	Settled fly ash in pond	Water to bottom ash hopper	Slurry from bottom ash crusher	Water to bottom ash slurry
1	Total stream, lb/hr	2,280	93,950	50,900	63,380	98,810
2						
3	Stream components, lb/hr					
4	Ash	570	49,740	3	12,480	7
5	Water	1,710	44,210	50,900	50,900	98,800
6	Air					
7						
8	$Ft^3/min, 60^\circ F$					
9	Gal/min	4		102	114	198
10	Percent solids	25	53		20	

	Stream No.	26	27	28	29	30
	Description	Bottom ash slurry from pump	Bottom ash utilization	Overflow water from bottom ash pond	Settled bottom ash in pond	Overflow water to treatment
1	Total stream, lb/hr	162,190	0	138,830	23,360	692,460
2						
3	Stream components, lb/hr					
4	Ash	12,490		120	12,370	620
5	Water	149,700		138,710	10,990	691,840
6	Air					
7						
8	$Ft^3/min, 60^\circ F$					
9	Gal/min	312		278		1,384
10	Percent solids	7.7			53	

	Stream No.	31	32	33		
	Description	Water treatment reagents	Water recycle to plant	Makeup water		
1	Total stream, lb/hr	100	690,280	55,070		
2						
3	Stream components, lb/hr					
4	Ash		50			
5	Water		690,230	55,070		
6	Air					
7	H_2SO_4	100				
8	$Ft^3/min, 60^\circ F$					
9	Gal/min	0.1	1,380	110		
10	Percent solids					

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

TABLE 10. EQUIPMENT LIST, DESCRIPTION, AND MATERIAL COST

BASE CASE 2 - DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

Item (number): description	Material cost, delivered, 1982 k$
Area 1--Fly Ash Collection and Transfer	
1. Economizer ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 15 ft wide x 16 ft deep, thermally isolated design, constructed of 1/2-in. carbon steel plate	27
2. Air heater ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 7 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, insulated	21
3. ESP ash hoppers (32): Inverted pyramid-type hopper, 18 ft long x 12 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, heat traced and insulated	373
4. Package-unit fly ash collecting and conveying system comprisng (1):	228
a. Vacuum pneumatic conveying lines for economizer-air heater ash and ESP ash (2): Pipelines and pipe fittings for vacuum pneumatic conveyance of fly ash, 25 ton/hr conveying capacity with 600-ft equivalent length system, 6-in. I.D. branch lines and 8-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard® or equivalent pipe fittings	
b. Fly ash and air inlet valves (40): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 6-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	
c. Line segregating valves (10): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 6-in. I.D. port, cast iron body, stainless steel slide gate	
d. Vacuum breaker valves (2): Vacuum breaker valve for control of vacuum in main conveying line to hydraulic exhauster, 8-in. I.D. port, cast iron body	

(continued)

TABLE 10 (continued)

Item (number): description	Material cost, delivered, 1982 k$
e. Hydraulic exhausters for vacuum pneumatic conveying system (2): Vacuum producing hydraulic exhauster with 8-in. I.D. air-ash inlet, 8-in. I.D. water connection, and 10-in. I.D. discharge, cast iron body with 250 psi water ejector head, chromium-iron alloy air-ash inlet liner, stainless steel water nozzle tips, ceramic-lined venturi throat; vertical installation, tapped for vacuum and pressure gauges	
f. System control unit (2): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and water to the hydraulic exhauster; includes gauges for manual reading and override switches for manual operation	
5. Water supply pumps for hydraulic exhausters (4 + 1 spare): Centrifugal pump, 600 gpm, 480-ft head, carbon steel body and impeller; 125 hp (costed 75% in Area 1 and 25% in Area 2)	57
Total, Area 1	706
Area 2--Fly Ash Conveyance to Disposal Site	
1. Water supply pumps for fly ash conveyance (4 + 1 spare): Same pumps as in Area 1, Item 5 (costed 25% in Area 2 and 75% in Area 1)	19
2. Air separator (1): Baffle-type cylindrical air separator tank with cone bottom, dual 8-in. I.D. inlets and single 12-in. I.D. slurry outlet, 8-ft I.D. carbon steel shell with 30-mm basalt lining	25
3. One-mile slurry pipeline to pond (1 + 1 spare): Pipeline comprising 132 40-ft-long sections of flanged steel pipe, 12-in. I.D., schedule 80 carbon steel and six elbows or bends, 12-in. I.D., schedule 80 I.D. hardened steel	(366)a
Total, Area 2	44

(continued)

TABLE 10 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 3--Fly Ash Disposal Site	
1. Fly ash pond (1): Pond, 3,011 ft square x 17.3 ft deep, 1-ft-thick clay liner, earthen perimeter dikes and 2,193-ft-long divider dike graded on top for use as service roads, pond area of 244 acres, pond volume of 5,537,000 yd^3, topsoil storage of 12.2 acres contiguous with topsoil storage for adjacent bottom ash pond, office trailer and equipment storage area common for fly ash and adjacent bottom ash pond, pond periphery monitored by three monitoring wells, fly ash pond isolated by 6-ft-high security fence which surrounds entire disposal site	(8,509)[a]
Total, Area 3	0
Area 4--Fly Ash Water Treatment and Recycle of Water (Costed 80% in Area 4 and 20% in Area 8)	
1. Sulfuric acid storage tank for pH control of water to discharge (1): Cylindrical steel tank 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2
2. Metering pump for sulfuric acid (1 + 1 spare): Positive displacement metering pump 0.01 to 1 gpm, 0 psig, Carpenter 20® alloy or similar corrosion resistance to 93% sulfuric acid; 0.25 hp flow rate controlled by a pH controller	2
3. Agitator for mixing of treated water (1): Agitator with 24-in.-diameter nickel-chromium blade; 5 hp	3
4. Pump for solids slurry from water treatment (1 + 1 spare): Centrifugal pump, 5 gpm, 20 psig, 1 carbon steel body and impeller, 0.25 hp	1
5. Chemical storage and preparation facility (1): Building 25 ft x 25 ft for storage and preparation of lime and soda ash water softening agents; includes concrete floor, storage bins, and 1,000 gal makeup and slaking tank with agitator; 10 hp	32
6. Package-unit water softener (1): Cold lime water softening unit, 34 ft long x 12 ft wide, 460 gpm capacity, carbon steel, 2 hp	50

(continued)

TABLE 10 (continued)

Item (number): description	Material cost, delivered, 1982 k$
7. Pumps for return water to plant (2): Centrifugal pump, 800 gpm, 200-ft head, carbon steel body and impeller; 75 hp	21
8. Return water pipeline (1): One-mile pipeline of welded steel pipe including six elbows or bends, 12 in. I.D., schedule 40 carbon steel	(120)[a]
9. Return water storage tank (1): Cylindrical steel tank, 50 ft diameter x 25 ft high, 370,000 gal capacity, open top, flat bottom, carbon steel	44
Total, Area 4	155
Area 5--Bottom Ash Collection and Transfer	
1. Water supply pumps for bottom ash hopper and slurry (2 + 1 spare): Centrifugal pump, 600 gpm, 250-ft head, carbon steel body and impeller, 75 hp	34
2. Bottom ash hopper assembly (1): Double-V hopper with 3,320 ft^3 capacity for 12-hr ash containment, supported independently of furnace-boiler and mated to furnace through a water seal trough spanning the furnace seal plate, hopper body of 3/8-in.-thick carbon steel plate, hopper lined with monolithic refractory 9 in. thick in upper section and 6 in. thick in lower section, stainless steel seal trough and overflow weirs, assembly includes poke doors, lighted observation windows, access doors and hydraulically operated ash exit doors; each V-section of hopper includes two hopper-type, double-roll grinders with cast iron body and 10-in.-diameter x 2-ft-long manganese steel rolls; 60 hp	352
Total, Area 5	386
Area 6--Bottom Ash Conveyance to Disposal Site	
1. Slurry pumps for pipeline conveyance (1 + 1 spare): Centrifugal slurry pump, 1,440 gpm, 350-ft head, Ni-Hard liner and impeller, 250-hp motor	57
2. Shutoff and crossover valves (10); Air-operated gate valve, 8-in. I.D. port, Ni-Hard	23

(continued)

TABLE 10 (continued)

Item (number): description		Material cost, delivered, 1982 k$
3.	One-mile basalt-lined slurry pipeline to pond, normal use (1): Pipeline comprising 294 18-ft-long sections of flanged, basalt-lined steel pipe, 8 in. I.D. and six basalt-lined elbows or bends, 8 in. I.D.	(373)[a]
4.	Spare slurry pipeline to pond (1): Pipeline comprising 132 40-ft-long sections of flanged steel pipe, 8 in. I.D., schedule 80, carbon steel and six hardened steel elbows or bends, 8 in. I.D.	(93)[a]
5.	Pipeline agitators (2): Agitator with single horizontal tooth roll, cast iron body, manganese steel roll and wear plate; 25 hp	30
	Total, Area 6	110
Area 7--Bottom Ash Disposal Site		
1.	Bottom ash pond (1): Pond, 1,699 ft square x 14.0 ft deep, with 1-ft-thick clay liner, earthen perimeter dikes and 1,215-ft-long divider dike graded on top for use as service roads, pond area of 85 acres, pond volume of 1,389,000 yd^3, topsoil storage of 3.1 acres contiguous with topsoil storage for adjacent fly ash pond, office trailer and equipment storage are common for bottom ash and adjacent fly ash pond, pond periphery monitored by two monitoring wells, bottom ash pond isolated by 6-ft-high security fence which surrounds entire disposal site	(2,127)[a]
	Total, Area 7	0
Area 8--Bottom Ash Water Treatment and Recycle of Water (Costed 20% in Area 8 and 80% in Area 4)		
1.	Sulfuric acid storage tank for pH control of water to discharge (1): Same tank as in Area 4, Item 1	0.5
2.	Metering pump for sulfuric acid (1): Same tank as in Area 4, Item 2	0.5
3.	Agitator for mixing of treated water (1): Same agitator as in Area 4, Item 3	0.75

(continued)

TABLE 10 (continued)

Item (number): description	Material cost, delivered, 1982 k$
4. Pump for solids slurry from water treatment (1 + 1 spare): Same pump as in Area 4, Item 4	0.25
5. Chemical storage and preparation facility (1): Same building as in Area 4, Item 5	8
6. Package-unit water softener (1): Same softener as in Area 4, Item 6	13
7. Pumps for return water to plant (2): Same pumps as in Area 4, Item 7	5
8. Return water pipeline (1): Same pipeline as in Area 4, Item 8	(30)[a]
9. Return water storage tank (1): Same tank as in Area 4, Item 9	11
Total, Area 8	39
Total, Base Case 2	1,440

[a] Costs shown in parentheses are informational and are not included in area or base case totals for equipment material costs.

water supplied to the fly ash hydraulic exhausters and the bottom ash hopper and sluicing pump is obtained from a hold tank containing recycled pond water and makeup water.

Ash Ponds

The same pond design and operation is used, as in base case 1. After flowing through the pH treatment flume, however, the water is collected in a catchment basin. Four-fifths of the water is pumped directly back to the power plant through a 12-inch steel pipeline. One-fifth of the water is passed through a package-unit water treatment plant at the pond site before entering the pipeline. The plant is essentially a cold lime - soda ash system designed primarily to reduce gypsum hardness and avoid scaling. Metered quantities of lime and soda ash are mixed with the water to reduce the calcium content by 90%. An initial 500 mg/L calcium concentration is assumed for the pond effluent, based on TVA data (80). About 275 gpm of water is treated on a 24-hour average but the water treatment plant is sized for 460 gpm to accommodate the higher peak loads associated with the intermittent ash transportation cycles. In all, a 24-hour average of about 1,400 gpm of water, including treated and untreated water, is returned to the ash transportation system.

The returned water is stored in a 370,000 gallon surge tank, providing a capacity of about 4-1/2 hours at average rates and about 2 hours for simultaneous transportation of fly ash and bottom ash. Water trapped in the settled sediments of the ash pond constitutes about 7% of the transportation requirements. This water is replaced with water from the power plant river water intakes.

BASE CASE 3 - HOLDING PONDS AND LANDFILL FOR NONHARDENING ASH

Base case 3 represents a disposal practice in which wet sluicing and ponding is used for initial ash collection, followed by dredging, draining, and landfill disposal of the ponded ash. This practice can be used if construction of large ponds is impractical or undesirable. Typical applications are for power plants that have limited available land and have exhausted existing ponds or have added new units. The flow diagram, disposal site plan, and plot plan for base case 3 are shown in Figures 13, 14, and 15. The material balance is shown in Table 11 and the equipment list is shown in Table 12.

In this base case the ash collection method and transportation to the ponds are the same as those used in base case 1 except that the ponds are one-fourth mile from the power plant. The fly ash is collected from the hoppers with a vacuum pneumatic conveying system using hydraulic exhausters and flows by gravity to the fly ash pond. In base case 3, the shorter conveying distance to the pond permits a lower elevation for the hydraulic exhausters and air separator and a lower head pressure for their water supply pumps. Bottom ash is sluiced from the bottom ash hoppers and pumped to the bottom ash pond using a jet pump. The jet pump is used instead of a centrifugal pump

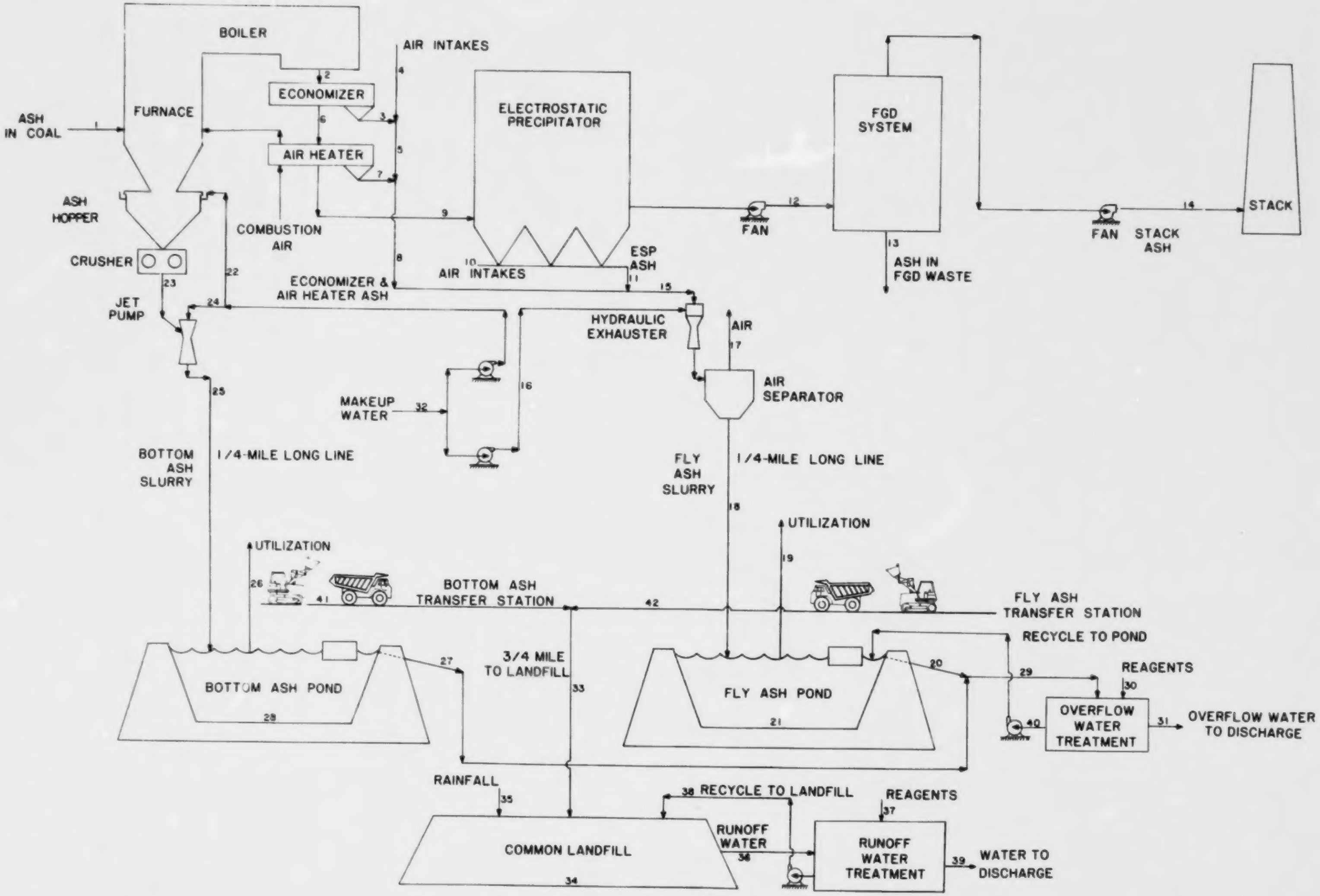
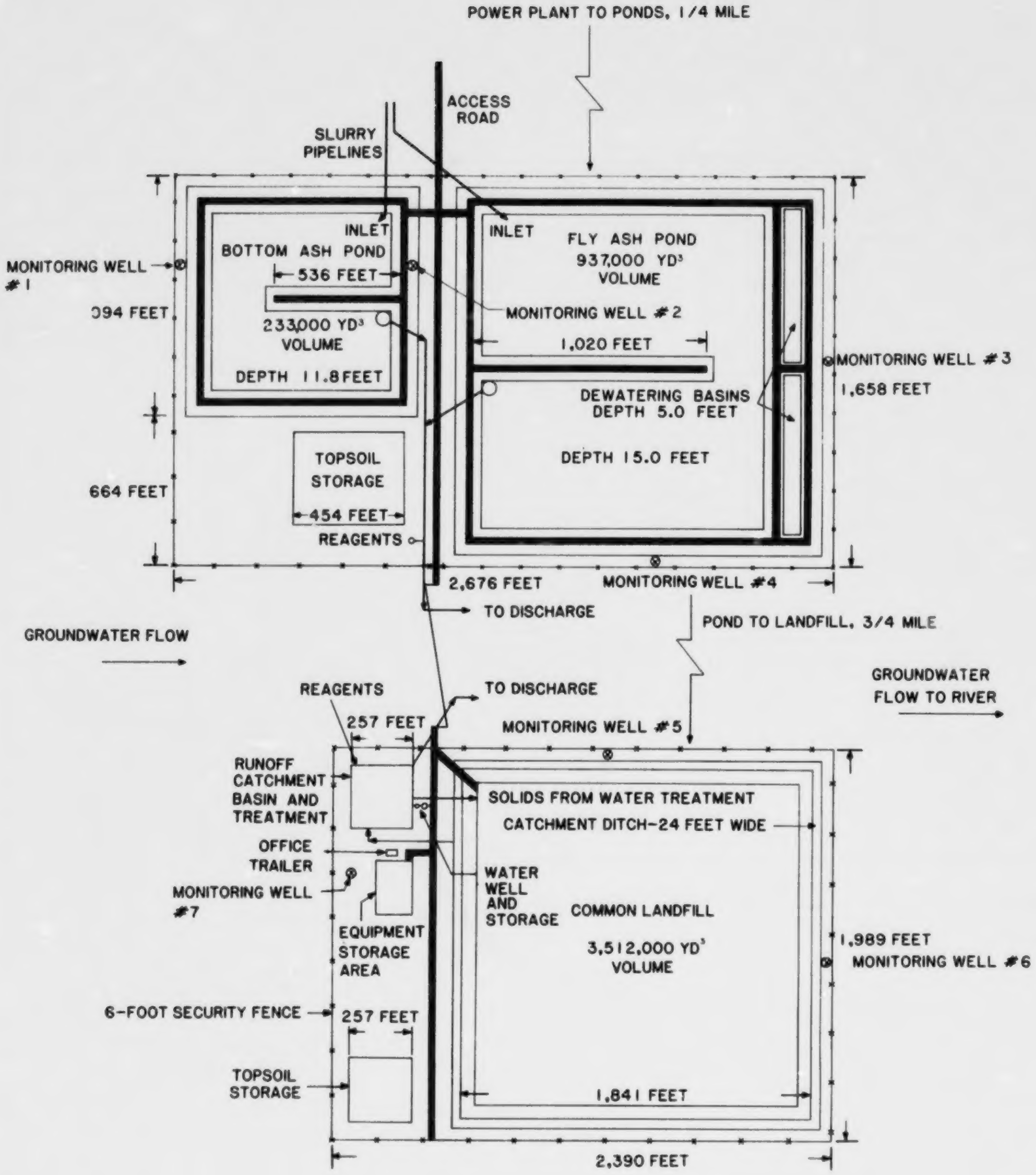

ASH IN COAL
1
FURNACE
BOILER
2
ECONOMIZER
6
AIR HEATER
3
4
5
7
AIR INTAKES
ASH HOPPER
COMBUSTION AIR
9
CRUSHER
23
22
JET PUMP
24
8
ECONOMIZER & AIR HEATER ASH
ELECTROSTATIC PRECIPITATOR
10
AIR INTAKES
ESP ASH
11
15
FAN
12
FGD SYSTEM
13
ASH IN FGD WASTE
FAN
STACK ASH
14
STACK
HYDRAULIC EXHAUSTER
AIR
17
AIR SEPARATOR
MAKEUP WATER
32
16
25
BOTTOM ASH SLURRY
1/4-MILE LONG LINE
FLY ASH SLURRY
1/4-MILE LONG LINE
18
UTILIZATION
19
UTILIZATION
26
41
BOTTOM ASH TRANSFER STATION
42
FLY ASH TRANSFER STATION
RECYCLE TO POND
BOTTOM ASH POND
28
27
3/4 MILE TO LANDFILL
33
FLY ASH POND
21
20
29
REAGENTS
30
40
OVERFLOW WATER TREATMENT
31
OVERFLOW WATER TO DISCHARGE
RAINFALL
35
38
RECYCLE TO LANDFILL
REAGENTS
37
COMMON LANDFILL
34
RUNOFF WATER
36
RUNOFF WATER TREATMENT
39
WATER TO DISCHARGE

Figure 13. Flow diagram. Base case 3, holding ponds and landfill for nonhardening ash.


POWER PLANT TO PONDS, 1/4 MILE
ACCESS ROAD
SLURRY PIPELINES
INLET
BOTTOM ASH POND
536 FEET
233,000 YD³
VOLUME
DEPTH 11.8 FEET
MONITORING WELL #1
994 FEET
664 FEET
TOPSOIL STORAGE
454 FEET
REAGENTS
INLET
FLY ASH POND
937,000 YD³
VOLUME
MONITORING WELL #2
1,020 FEET
DEWATERING BASINS
DEPTH 5.0 FEET
DEPTH 15.0 FEET
MONITORING WELL #3
1,658 FEET
2,676 FEET
MONITORING WELL #4
TO DISCHARGE
POND TO LANDFILL, 3/4 MILE
GROUNDWATER FLOW
GROUNDWATER FLOW TO RIVER
REAGENTS
TO DISCHARGE
257 FEET
MONITORING WELL #5
RUNOFF CATCHMENT BASIN AND TREATMENT
SOLIDS FROM WATER TREATMENT
CATCHMENT DITCH-24 FEET WIDE
OFFICE TRAILER
MONITORING WELL #7
WATER WELL AND STORAGE
COMMON LANDFILL
3,512,000 YD³
VOLUME
EQUIPMENT STORAGE AREA
1,989 FEET
MONITORING WELL #6
6-FOOT SECURITY FENCE
257 FEET
TOPSOIL STORAGE
1,841 FEET
2,390 FEET

TOTAL DISPOSAL SITE AREA, 212 ACRES
TOTAL POND SITE AREA, 102 ACRES
TOTAL LANDFILL SITE AREA, 110 ACRES

Figure 14. Disposal site. Base case 3, holding ponds and landfill for nonhardening ash.

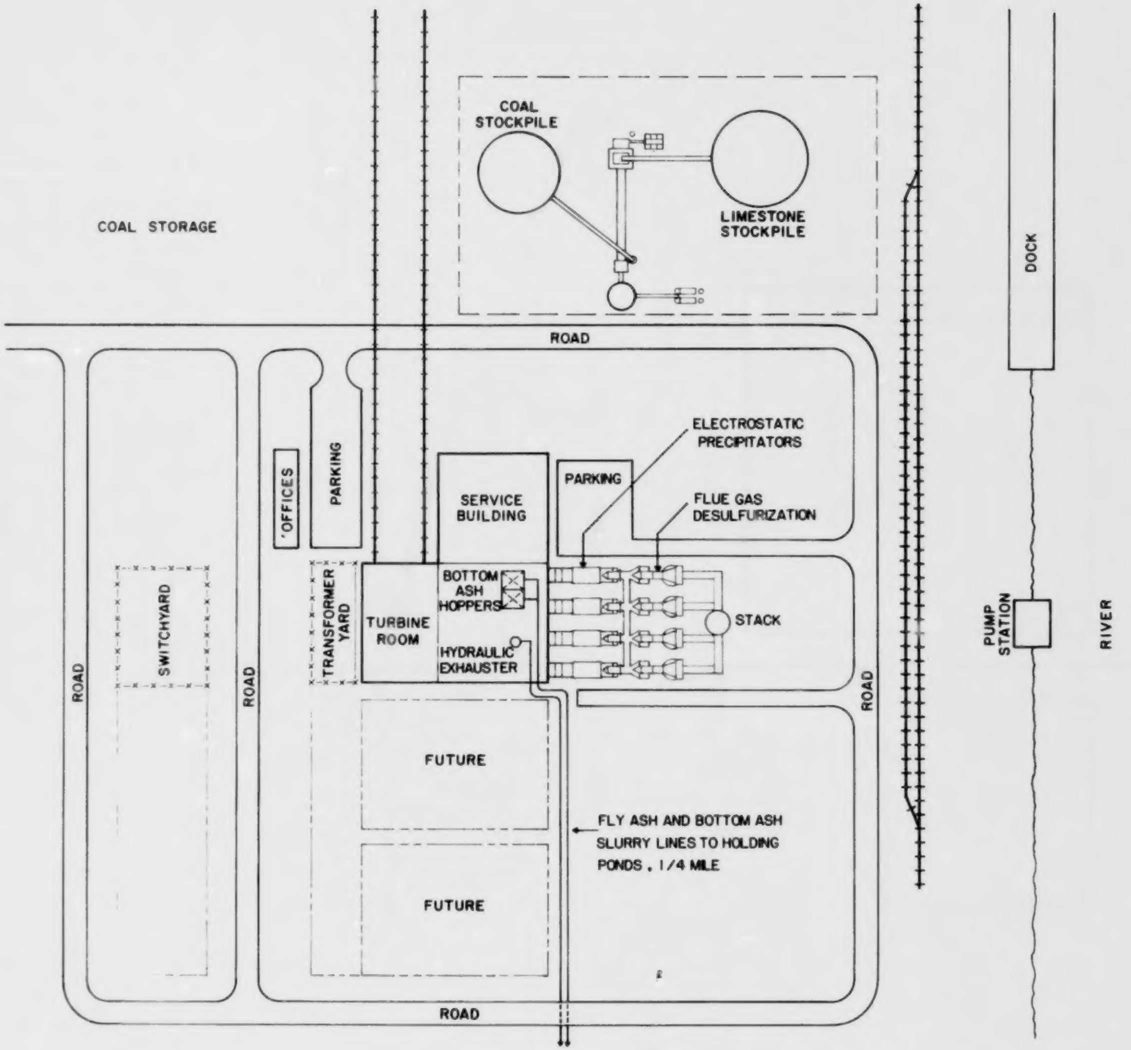

COAL STORAGE
COAL STOCKPILE
LIMESTONE STOCKPILE
DOCK
ROAD
ELECTROSTATIC PRECIPITATORS
PARKING
SERVICE BUILDING
FLUE GAS DESULFURIZATION
'OFFICES
PARKING
BOTTOM ASH HOPPERS
TURBINE ROOM
TRANSFORMER YARD
HYDRAULIC EXHAUSTER
STACK
PUMP STATION
RIVER
SWITCHYARD
ROAD
ROAD
ROAD
FUTURE
FUTURE
FLY ASH AND BOTTOM ASH SLURRY LINES TO HOLDING PONDS, 1/4 MILE
ROAD

Figure 15. Plot plan. Base case 3, holding ponds and landfill for nonhardening ash.

TABLE 11. MATERIAL BALANCE

BASE CASE 3 - HOLDING PONDS AND LANDFILL FOR NONHARDENING ASH

	Stream No.	1	2	3	4	5
	Description	Coal ash to furnace	Ash to economizer	Ash collected from economizer	Air intake to economizer ash pneumatic system	Economizer ash in pneumatic system
1	Total stream, lb/hr	62,400	49,920	1,560	100	1,660
2						
3	Stream components, lb/hr					
4	Ash	62,400	49,920	1,560		1,560
5	Water					
6	Air				100	100
7						
8	Ft^3/min, 60^{o}F				22	
9	Gal/min					
10	Percent solids					

	Stream No.	6	7	8	9	10
	Description	Ash to air heater	Ash collected from air heater	Economizer-air heater ash in pneumatic system	Ash to ESP	Air intake to ESP ash pneumatic system
1	Total stream, lb/hr	48,360	1,560	3,220	46,800	1,390
2						
3	Stream components, lb/hr					
4	Ash	48,360	1,560	3,120	46,800	
5	Water					
6	Air			100		1,390
7						
8	Ft^3/min, 60^{o}F					303
9	Gal/min					
10	Percent solids					

	Stream No.	11	12	13	14	15
	Description	ESP ash in pneumatic system	Ash to FGD system	Ash in FGD waste	Ash to stack	Ash to hydraulic exhauster
1	Total stream, lb/hr	47,900	285	143	142	51,120
2						
3	Stream components, lb/hr					
4	Ash	46,510	285	143	142	49,630
5	Water					
6	Air	1,390				1,490
7						
8	Ft^3/min, 60^{o}F					
9	Gal/min					
10	Percent solids					

	Stream No.	16	17	18	19	20
	Description	Water to hydraulic exhauster	Exhaust air from hydraulic exhauster	Fly ash slurry from hydraulic exhauster	Fly ash utilization	Overflow water from fly ash pond
1	Total stream, lb/hr	595,600	1,490	645,230	0	581,240
2						
3	Stream components, lb/hr					
4	Ash			49,630		500
5	Water	595,600		595,600		580,740
6	Air		1,490			
7						
8	Ft^3/min 60^{o}F		325			
9	Gal/min	1,190		1,241		1,162
10	Percent			7.7		

(continued)

TABLE 11 (continued)

Stream No.		21	22	23	24	25
Description		Settled fly ash in pond	Water to bottom ash hopper	Slurry from bottom ash crusher	Water to jet pump	Bottom ash slurry from pump
1	Total stream, lb/hr	93,880	50,900	63,380	98,800	162,180
2						
3	Stream components, lb/hr					
4	Ash	49,700		12,480		12,480
5	Water	44,180	50,900	50,900	98,800	149,700
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min		102	114	198	312
10	Percent solids	53		20		7.7

Stream No.		26	27	28	29	30
Description		Bottom ash utilization	Overflow water from bottom ash pond	Settled bottom ash in pond	Overflow water to treatment	Reagents
1	Total stream, lb/hr	0	148,450	23,350	729,690	20
2						
3	Stream components, lb/hr					
4	Ash		120	12,360	620	
5	Water		148,330	10,990	729,070	
6	Air					
7	H_2SO_4					20
8	Ft^3/min, 60°F					
9	Gal/min		297		1,460	0.02
10	Percent solids			53		

Stream No.		31	32	33	34	35
Description		Pond overflow water to discharge	Makeup water	Combined ash to landfill	Common landfill	Rainfall to landfill
1	Total stream, lb/hr	729,390	745,300	80,000	74,470	84,610
2						
3	Stream components, lb/hr					
4	Ash	50		62,060	62,060	
5	Water	727,340	745,300	17,940	12,410	84,610
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min	1,455	1,491			169
10	Percent solids			78	83	

Stream No.		36	37	38	39	40
Description		Landfill runoff water to treatment	Reagents for landfill water treatment	Solids from water treatment	Treated landfill runoff to discharge	Solids from overflow treatment
1	Total stream, lb/hr	91,900	60	1,760	90,200	2,280
2						
3	Stream components, lb/hr					
4	Ash	50		45	5	570
5	Water	91,850		1,710	90,200	1,710
6	Air					
7	H_2SO_4		60			
8	Ft^3/min, 60°F					
9	Gal/min	174	0.06	4	180	4
10	Percent solids					

(continued)

TABLE 11 (continued)

	Stream No.	41	42			
	Description	Bottom ash to landfill	Fly ash to landfill			
1	Total stream, lb/hr	13,730	66,270			
2						
3	Stream components, lb/hr					
4	Ash	12,360	49,700			
5	Water	1,370	16,570			
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min					
10	Percent solids	90	75			

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

TABLE 12. EQUIPMENT LIST, DESCRIPTION, AND MATERIAL COST

BASE CASE 3 - HOLDING PONDS AND LANDFILL FOR NONHARDENING ASH

Item (number): description	Material cost, delivered, 1982 k$
Area--1 Fly Ash Collection and Transfer	
1. *Economizer ash hoppers* (4): Inverted pyramid-type hopper, 15 ft long x 15 ft wide x 16 ft deep, thermally isolated design, constructed of 1/2-in. carbon steel plate	27
2. *Air heater ash hoppers* (4): Inverted pyramid-type hopper, 15 ft long x 7 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, insulated	21
3. *ESP ash hoppers* (32): Inverted pyramid-type hopper, 18 ft long x 12 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, heat traced and insulated	373
4. *Package-unit fly ash collecting and conveying system comprising* (1):	228
a. *Vacuum pneumatic conveying lines for economizer air heater ash and ESP ash* (2): Pipelines and pipe fittings for vacuum pneumatic conveyance of fly ash, 25 ton/hr conveying capacity with 600-ft equivalent length system, 6-in. I.D. branch lines and 8-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard® or equivalent pipe fittings	
b. *Fly ash and air inlet valves* (40): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 6-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	
c. *Line segregating valves* (10): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 6-in. I.D. port, cast iron body, stainless steel slide gate	
d. *Vacuum breaker valves* (2): Vacuum breaker valve for control of vacuum in main conveying line to hydraulic exhauster, 8-in. I.D. port, cast iron body	

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
e. Hydraulic exhausters for vacuum pneumatic conveying system (2): Vacuum producing hydraulic exhauster with 8-in. I.D. air-ash inlet, 8-in. I.D. water connection, and 10-in. I.D. discharge, cast iron body with 250 psi water ejector head, chromium-iron alloy air-ash inlet liner, stainless steel water nozzle tips, ceramic-lined venturi throat; vertical installation, tapped for vacuum and pressure gauges	
f. System control unit (2): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and water to hydraulic exhauster; includes gauges for manual reading and override switches for manual operation	
5. Water supply pumps for hydraulic exhausters (4): Centrifugal pump, 600 gpm, 420-ft head, carbon steel body and impeller; 110 hp (costed 80% in Area 1 and 20% in Area 2)	57
Total, Area 1	706
Area 2--Fly Ash Conveyance to Disposal Site	
1. Water supply pumps for fly ash conveyance (4): Same pumps as in Area 1, Item 5 (costed 20% in Area 2 and 80% in Area 1)	14
2. Air separator (1): Baffle-type cylindrical air separator tank with cone bottom, dual 8-in. I.D. inlets and single 12-in. I.D. slurry outlet, 8-ft I.D. carbon steel shell with 30-mm basalt lining	25
3. Quarter-mile slurry pipeline to pond (1 + 1 spare): Pipeline comprising 33 40-ft-long sections of flanged steel pipe, 12-in. I.D., schedule 80 carbon steel and six elbows or bends, 12-in. I.D., schedule 80 I.D. hardened steel	(92)[a]
4. Front-end loaders for loading trucks at fly ash holding ponds (2): 977L Caterpillar or equivalent, track-type front-end bucket loader, 3-yd^3 bucket, 10-ft lift, 190-hp diesel engine	334

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
5. Trucks for hauling ash from holding ponds to landfill (2 + 1 spare): Tandem-axle 4 rear-wheel-drive dump truck with ash-haul body, 20-yd^3 capacity, 44,000-lb suspension, 6 forward-speed manual transmission, 237-hp diesel engine (costed 80% in Area 2 and 20% in Area 6)	221
6. Service truck for fuel, lubricants, and field service (1): Service truck with 500-gal cargo tank for diesel fuel and cargo space for lubricants and other field service items (costed 80% in Area 2 and 20% in Area 6)	20
Total, Area 2	604
Area 3--Fly Ash Disposal Site	
1. Fly ash holding pond with 5-yr capacity (1): Fly ash holding pond, 1,461 ft square, with earthen perimeter dike and 1-ft-thick clay liner; holding pond subdivided by 1,461-ft-long divider dike into 15-ft-deep settling pond with 1,020-ft-long median dike and into 100-ft-wide x 5-ft-deep dewatering basin with 100-ft-long median dike across middle; all interior dikes of bottom ash; all dikes graded on top for 24-ft-wide service roads; topsoil storage of 3.8 acres contiguous with topsoil storage for adjacent bottom-ash pond; holding-pond periphery monitored by three monitoring wells; holding pond enclosed by 6-ft-high security fence which surrounds entire pond disposal site	(2,534)[a]
2. Common landfill for 25-yr capacity (1): Common landfill for fly ash and bottom ash, 1,841-ft square with 1-ft-thick clay liner, volume of 3,512,000 yd^3, constructed in one 20-ft lift with edge sloped upward at 1-vertical to 2-horizontal (27°), edges and top covered as filled with 1/2-ft-thick layer of clay and 1-1/2-ft-thick layer of topsoil, 20 ft finished height at edge with top sloped upward to center of landfill at 1-vertical to 29-horizontal (2°), landfill surrounded by runoff and leachate collection ditch 24 ft wide x 2.5 ft deep with 1-ft-thick clay liner; ditch drains to 257-ft-square	(1,491)[a]

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
catchment basin with 1-ft-thick clay liner; site includes 257-ft-square topsoil storage area, office trailer with sanitary facilities, equipment storage area, 24-ft-wide access roads, onsite water supply well and three peripheral monitoring wells; overall landfill disposal site of 110 acres is surrounded by 6-ft-high security fence (costed 80% in Area 3 and 20% in Area 7)	
3. Dozer for moving ash and earth at landfill (2): D4E Caterpillar or equivalent, track-type with 10-ft-long U-shaped blade, 75-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	118
4. Compactor for ash at landfill (1): Vibratory sheepsfoot compactor, self-propelled, Raygo 420 C or equivalent (costed 80% in Area 3 and 20% in Area 7)	70
5. Tank truck for dust control at landfill (1): Tandem-axle 4 rear-wheel-drive tank truck with spray-nozzle boom attachment and pumping system, 2,000-gal fiberglass tank, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	33
6. Front-end loader for stripping and restoring topsoil (1): Caterpillar 950 or equivalent front-end bucket loader, 3-yd^3 bucket, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	93
7. Service truck for fuel, lubricants, and field service (1): Service truck with 500-gal cargo tank for diesel fuel and cargo space for lubricants and other field service items (costed 80% in Area 3 and 20% in Area 7)	20
Total, Area 3	[illegible]
Area 4--Fly Ash Water Treatment and Recycle of Water (Costed 80% in Area 4 and 20% in Area 8)	
1. Sulfuric acid storage tank for pH control of water (2): Cylindrical steel tank 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel	4

(continued)

TABLE 1[illegible] (continued)

Item (number): description	Material cost, delivered, 1982 k$
2. Metering pump for sulfuric acid (2): Positive displacement metering pump, 0.01 to 1 gpm, 0 psig with flow rate controlled by a pH controller, Carpenter 20® alloy or similar corrosion resistance to 93% sulfuric acid; 0.25 hp	4
3. Agitator for mixing of treated water (2): Agitator with 24-in.-diameter nickel-chromium blade; 5 hp	6
4. Pump for solids slurry from water treatment (2): Centrifugal pump, 5 gpm, 20 psig, carbon steel body and impeller, 0.25 hp	2
5. Automatic samplers for water to discharge (2): Automatic sampler with sample size controlled by flow rate, refrigerated storage of composite sample; all-weather housing	8
Total, Area 4	24
Area 5--Bottom Ash Collection and Transfer	
1. Water supply pumps for bottom ash hopper and jet pumps (2 + 1 spare): Centrifugal pump, 600 gpm, 250-ft head, carbon steel body and impeller, 75 hp (costed 34% in Area 5 and 66% in Area 6)	18
2. Bottom ash hopper assembly (1): Double-V hopper with 3,320-ft^3 capacity for 12-hr ash containment, supported independently of furnace-boiler and mated to furnace through a water seal trough spanning the furnace seal plate, hopper body of 3/8-in.-thick carbon steel plate, hopper lined with monolithic refractory 9-in. thick in upper section and 6-in. thick in lower section, stainless steel seal trough and overflow weirs, assembly includes poke doors, lighted observation windows, access doors and hydraulically operated ash exit doors; each V-section of hopper includes two hopper-type, double-roll grinders with cast iron body and 10-in.-diameter x 2-ft-long manganese steel rolls; 60 hp	352
Total, Area 5	370

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 6--Bottom Ash Conveyance to Disposal Site	
1. Water supply pumps for bottom ash jet pumps (2 + 1 spare): Same pumps as in Area 5, Item 1 (costed 66% in Area 6 and 34% in Area 5)	36
2. Jet pumps for bottom ash conveyance (2 + 2 spares): Jet ejector slurry pump, feed water capacity of 400 gpm at 250-ft head, outlet slurry capacity of 625 gpm at 120-ft head, Ni-Hard nozzles and throat	49
3. Shutoff and crossover valves (10): Air-operated gate valve, 8-in. I.D. port, Ni-Hard	23
4. Quarter-mile slurry pipeline to holding pond, normal use (1): Pipeline comprising 73 18-ft-long sections of flanged, basalt-lined steel pipe, 8-in. I.D. and 6 basalt-lined elbows or bends, 8-in. I.D.	(93)[a]
5. Spare slurry pipeline to holding pond (1): Pipeline comprising 33 40-ft-long sections of flanged steel pipe, 8-in. I.D., schedule 80 carbon steel and 6 hardened steel elbows or bends, 8-in. I.D.	(23)[a]
6. Front-end loader for loading trucks at bottom ash holding pond (1): Caterpillar 977L or equivalent, track-type front-end bucket loader, 3-yd^3 bucket, 10-ft lift, 190-hp diesel engine	167
7. Trucks for hauling ash from holding pond to landfill (2 + 1 spare): Same trucks as in Area 2, Item 5 (costed 20% in Area 6 and 80% in Area 2)	53
8. Service truck for fuel, lubricants, and field service (1): Same truck as in Area 2, Item 6 (costed 20% in Area 6 and 80% in Area 2)	5
Total, Area 6	333
Area 7--Bottom Ash Disposal Site	
1. Bottom ash holding pond for 5-yr capacity (1): Bottom ash holding pond, 815 ft square x 11.8 ft deep, with	(608)[a]

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
earthen perimeter dikes and 1-ft-thick clay liner; 536-ft-long bottom ash divider dike; all dikes graded on top for 24-ft-wide service roads, pond area of 15.2 acres, pond volume of 233,000 yd^3, topsoil storage of 0.9 acre contiguous with topsoil storage for adjacent fly ash pond, pond periphery monitored by two monitoring wells, bottom ash pond enclosed by 6-ft-high security fence which surrounds entire pond disposal site	
2. Common landfill for 25-yr capacity (1): Same landfill as in Area 3, Item 2 (costed 20% in Area 7 and 80% in Area 3)	(372)[a]
3. Dozer for moving ash and earth at landfill (1): Same dozer as in Area 3, Item 3 (costed 20% in Area 7 and 80% in Area 3)	30
4. Compactor for ash at landfill (1): Same compactor as in Area 3, Item 4 (costed 20% in Area 7 and 80% in Area 3)	18
5. Tank truck for dust control at landfill (1): Same truck as in Area 3, Item 5 (costed 20% in Area 7 and 80% in Area 3)	8
6. Front-end loader for stripping and replacing topsoil (1): Same loader as in Area 3, Item 6 (costed 20% in Area 7 and 80% in Area 3)	23
7. Service truck for fuel, lubricants, and field service (1): Same truck as in Area 3, Item 7 (costed 80% in Area 7 and 20% in Area 3)	5
Total, Area 7	84
Area 8--Bottom Ash Water Treatment and Recycle of Water (Costed 20% in Area 8 and 80% in Area 4)	
1. Sulfuric acid storage tank for pH control of water (2): Same tanks as in Area 4, Item 1	1
2. Metering pump for sulfuric acid (2): Same pumps as in Area 4, Item 2	1

(continued)

TABLE 12 (continued)

Item (number): description	Material cost, delivered, 1982 k$
3. Agitator for mixing of treated water (2): Same agitators as in Area 4, Item 3	1.5
4. Pump for solids slurry from water treatment (2): Same pumps as in Area 4, Item 4	0.5
5. Automatic samplers for water to discharge (2): Same samplers as in Area 4, Item 5	2
Total, Area 8	6
Total, Base Case 3	2,461

a. Costs shown in parentheses are informational and are not included in totals for equipment material cost.

because of the lower dynamic head of the bottom ash system in this system. With the exception of the jet pump, all equipment, rates, and procedures are identical to base case 1.

Ash Ponds

The same pond and pond site design is used, as in base case 1, but both ponds are designed for a five-year capacity. The pond site is situated one-fourth mile from the power plant and it occupies 102 acres, including working and storage areas. The flow rates to the ponds are identical to those of base case 1 and the treatment of the pond effluents is similar to that of base case 1.

The fly ash pond occupies a contained area of 55 acres and has a capacity of 0.9 million yd^3 of settled ash 15 feet deep when full. One side of the fly ash pond consists of two dewatering basins. These basins are separated from the main pond by a permeable dike constructed of bottom ash and the bottoms are elevated above the main pond bottom. Settled fly ash from the main pond is removed with a floating hydraulic dredge and pumped alternately into one of the two dewatering basins where it settles to 75% solids as the water drains back into the main pond.

The bottom ash pond occupies a contained area of 16 acres and has a capacity of 0.2 million yd^3 when filled to a depth of 12 feet. No dewatering basins are needed for bottom ash because it settles readily and supports mobile equipment.

Ash Removal and Transportation

Fly ash is removed from the dewatering basins and bottom ash from the bottom ash pond using track-type front loaders, loaded on trucks, and hauled three-fourths of a mile to the disposal site. A single landfill is used for both ashes. Two rear-dump, 44,000 lb, 20 yd^3, ash-haul-body trucks are used. The mobile equipment is sized for 1.5 times the ash production rate. The pond, trucking, and landfill disposal equipment is operated two shifts/day during the power plant operating year of 5500 hours. At the end of 25 years of operation ash removal operations are halted. The ponds are then allowed to fill to capacity during the final 5 years of power plant operation.

Landfill

The common landfill site occupies 110 acres, including topsoil storage, runoff control, and working areas. The filled area occupies 78 acres. The landfill is designed for a 25-year capacity of 3.5 million yd^3 using a 90 lb/ft^3 dry bulk density and 17% moisture for both types of ash. The design and operation are described in the premises. Sections of the landfill are prepared, filled, and covered progressively to minimize the disturbed area. Topsoil stripped from each new section is used to cover the previously filled section. The stripped section is lined with one foot of clay and covered with two feet of bottom ash which acts as a porous drainage base. The clay and ash base is designed to drain to a catchment basin about two acres in size, which also receives runoff from the perimeter ditches. The collected water, is augmented by well water when needed, is returned to the landfill and used for compaction moisture and revegetation irrigation.

The fly ash and bottom ash are placed in successive, compacted lifts to a center height of 51 feet. The ash is then covered with clay and topsoil and revegetated. The completed fill has side slopes of 1 vertical to 2 horizontal and a top sloping slightly upward to the center. Provision for monitoring wells, catchment basin water treatment, offices and equipment facilities, roads, and topsoil storage are provided. Two track-type dozers, a front-end loader, and a self-propelled compactor are used to prepare and maintain the site. A water truck is also provided for dust control.

BASE CASE 4 - DIRECT LANDFILLING OF NONHARDENING ASH

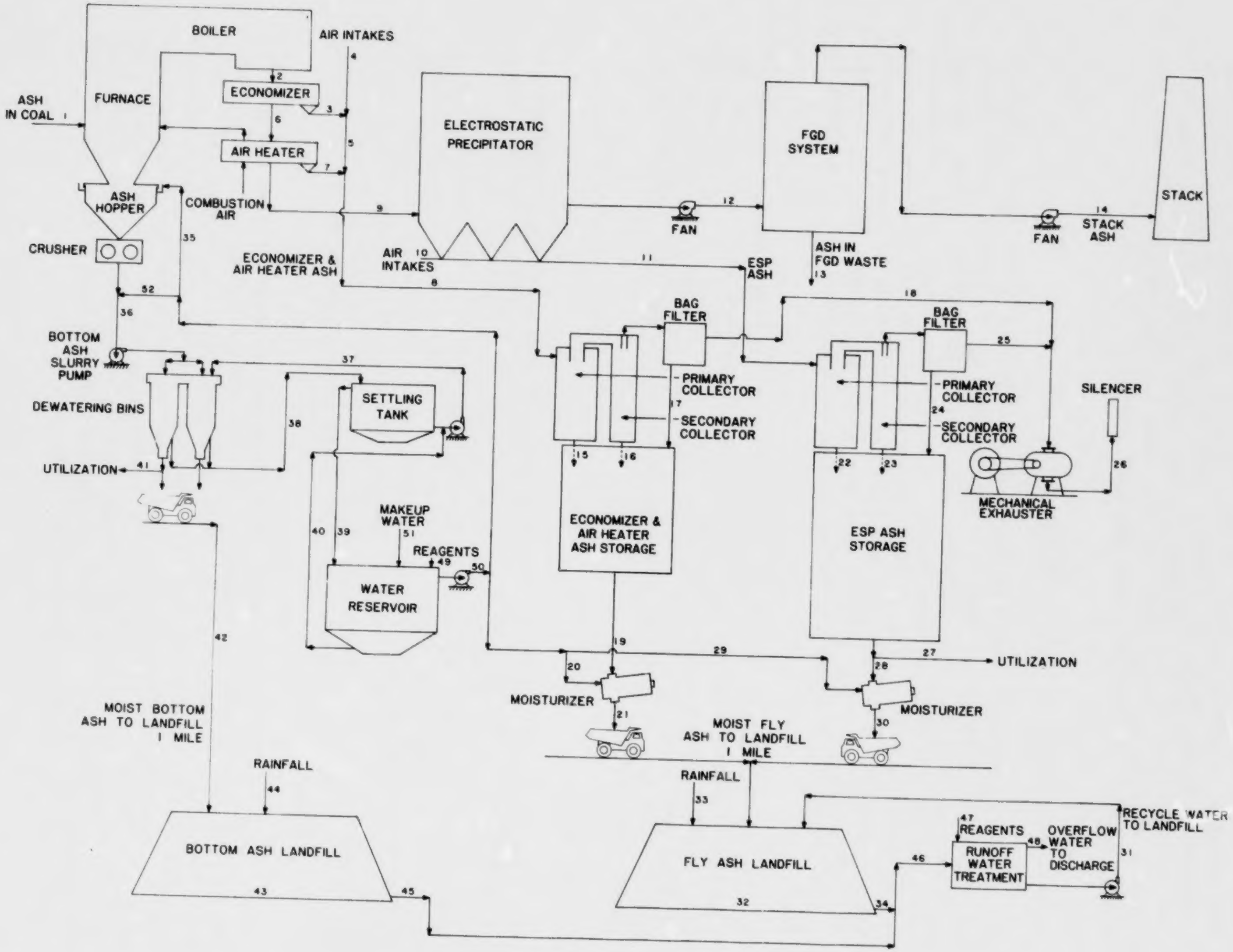
Base case 4 represents a common disposal practice in which the fly ash is collected dry and landfilled and the bottom ash is dewatered after being sluiced from the bottom ash hoppers and also landfilled. This method minimizes water use, reduces the amount of recycled water, and eliminates discharge of transportation water. Dry collection of fly ash also facilitates handling and improves its utilization potential. The flow diagram, disposal site plan, and plot plan for base case 4 are shown in Figures 16, 17, and 18. The material balance is shown in Table 13 and the equipment list is shown in Table 14.

Fly ash is collected in silos using a mechanically induced pneumatic vacuum system. It is removed from the silos, moistened and trucked to the landfill. Bottom ash sluiced from the bottom ash hoppers is dewatered in settling bins and also trucked to the landfill. At the disposal site fly as and bottom ash are segregated in separate landfills to improve their utilization potential.

Fly Ash Collection

The economizer, air heater, and ESP ash conveying system is similar to the vacuum pneumatic systems used in the previous base cases. The economizer and air heater ash is collected separately from the ESP ash, however. In addition, vacuum is applied by two lobe-type mechanical exhausters. Ash is removed from the conveying system upstream from the vacuum pumps in primary and secondary centrifugal separators followed by a fabric filter unit. The system is designed for a 19 in. Hg vacuum and a 1,500 sft^3/min air flow at an ash-to-air ratio of about 30 to 1. Automatic cycling controls are provided. The design capacity is 53 tons/day, permitting a 12 hr/day operating schedule.

The primary collectors consist of centrifugal separators that remove 83% of the ash in the conveying systems. The secondary centrifugal collectors increase the total removal to 97%. The remaining ash is removed in shaker-type fabric filters with a 1.5 aft^3/min/ft^2 filter area. The collected ash falls into cylindrical steel storage silos with 64-hour storage capacities. The silos are elevated for direct loading of trucks or rail cars and are equipped with fluidizing systems and filtered vents. The economizer and air heater ash silo is 16 feet in diameter and 18 feet high. The ESP ash silo is 38 feet in diameter and 50 feet high.


BOILER
AIR INTAKES
ASH IN COAL
FURNACE
ECONOMIZER
AIR HEATER
COMBUSTION AIR
ASH HOPPER
CRUSHER
ECONOMIZER & AIR HEATER ASH
ELECTROSTATIC PRECIPITATOR
AIR INTAKES
FAN
FGD SYSTEM
ASH IN FGD WASTE
FAN
STACK ASH
STACK
ESP ASH
BAG FILTER
PRIMARY COLLECTOR
SECONDARY COLLECTOR
BAG FILTER
PRIMARY COLLECTOR
SECONDARY COLLECTOR
SILENCER
MECHANICAL EXHAUSTER
BOTTOM ASH SLURRY PUMP
DEWATERING BINS
UTILIZATION
SETTLING TANK
MAKEUP WATER
REAGENTS
WATER RESERVOIR
ECONOMIZER & AIR HEATER ASH STORAGE
ESP ASH STORAGE
UTILIZATION
MOISTURIZER
MOISTURIZER
MOIST BOTTOM ASH TO LANDFILL 1 MILE
MOIST FLY ASH TO LANDFILL 1 MILE
RAINFALL
RAINFALL
BOTTOM ASH LANDFILL
FLY ASH LANDFILL
REAGENTS
RUNOFF WATER TREATMENT
OVERFLOW WATER TO DISCHARGE
RECYCLE WATER TO LANDFILL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
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52

Figure 16. Flow diagram. Base case 4, direct landfill of nonhardening ash.

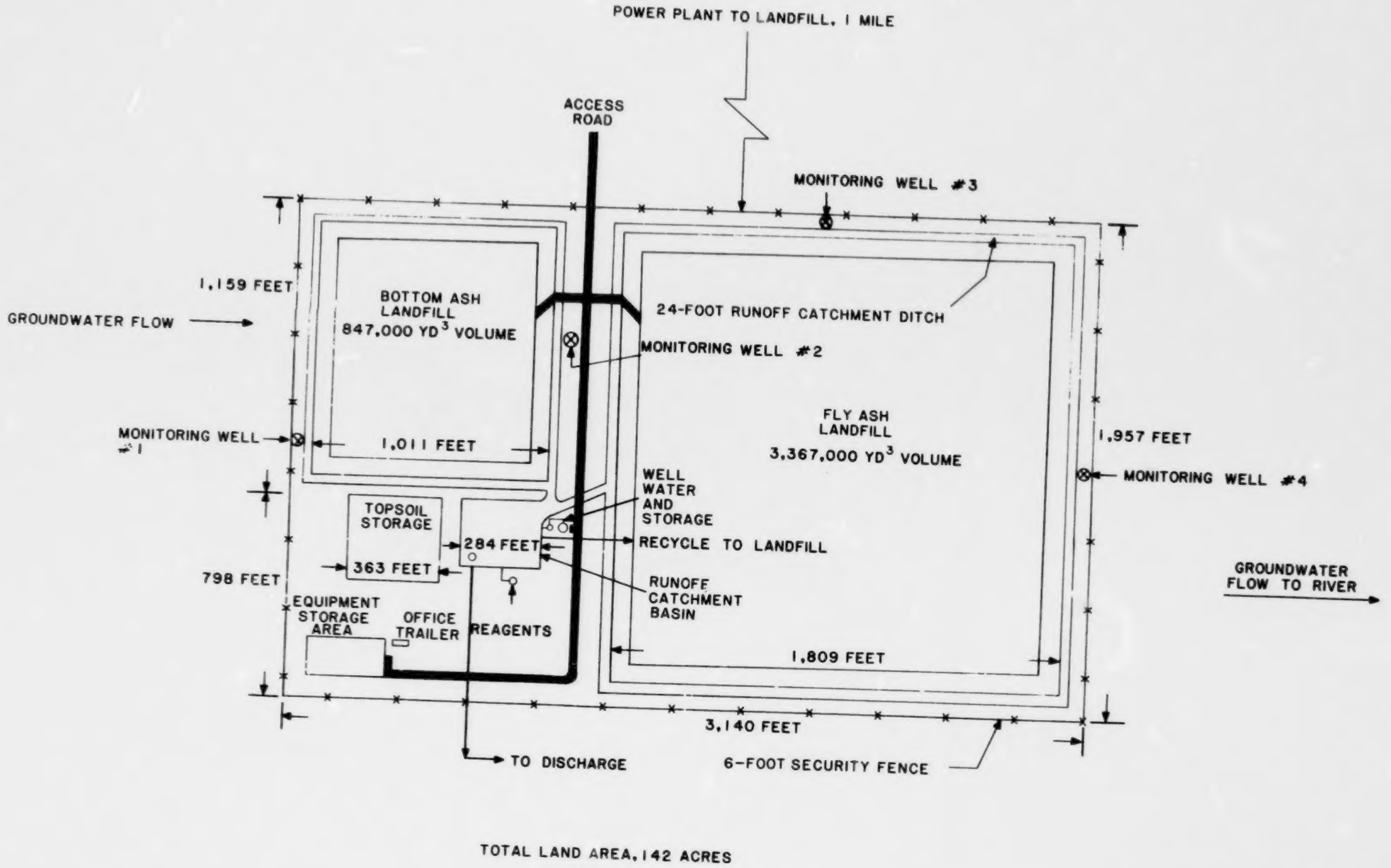

POWER PLANT TO LANDFILL, 1 MILE
ACCESS ROAD
MONITORING WELL #3
1,159 FEET
BOTTOM ASH LANDFILL 847,000 YD^3 VOLUME
24-FOOT RUNOFF CATCHMENT DITCH
GROUNDWATER FLOW
MONITORING WELL #2
FLY ASH LANDFILL 3,367,000 YD^3 VOLUME
MONITORING WELL #1
1,011 FEET
1,957 FEET
MONITORING WELL #4
WELL WATER AND STORAGE
TOPSOIL STORAGE
284 FEET
RECYCLE TO LANDFILL
363 FEET
798 FEET
RUNOFF CATCHMENT BASIN
GROUNDWATER FLOW TO RIVER
EQUIPMENT STORAGE AREA
OFFICE TRAILER
REAGENTS
1,809 FEET
3,140 FEET
TO DISCHARGE
6-FOOT SECURITY FENCE
TOTAL LAND AREA, 142 ACRES

Figure 17. Disposal site. Base case 4, direct landfill of nonhardening ash.

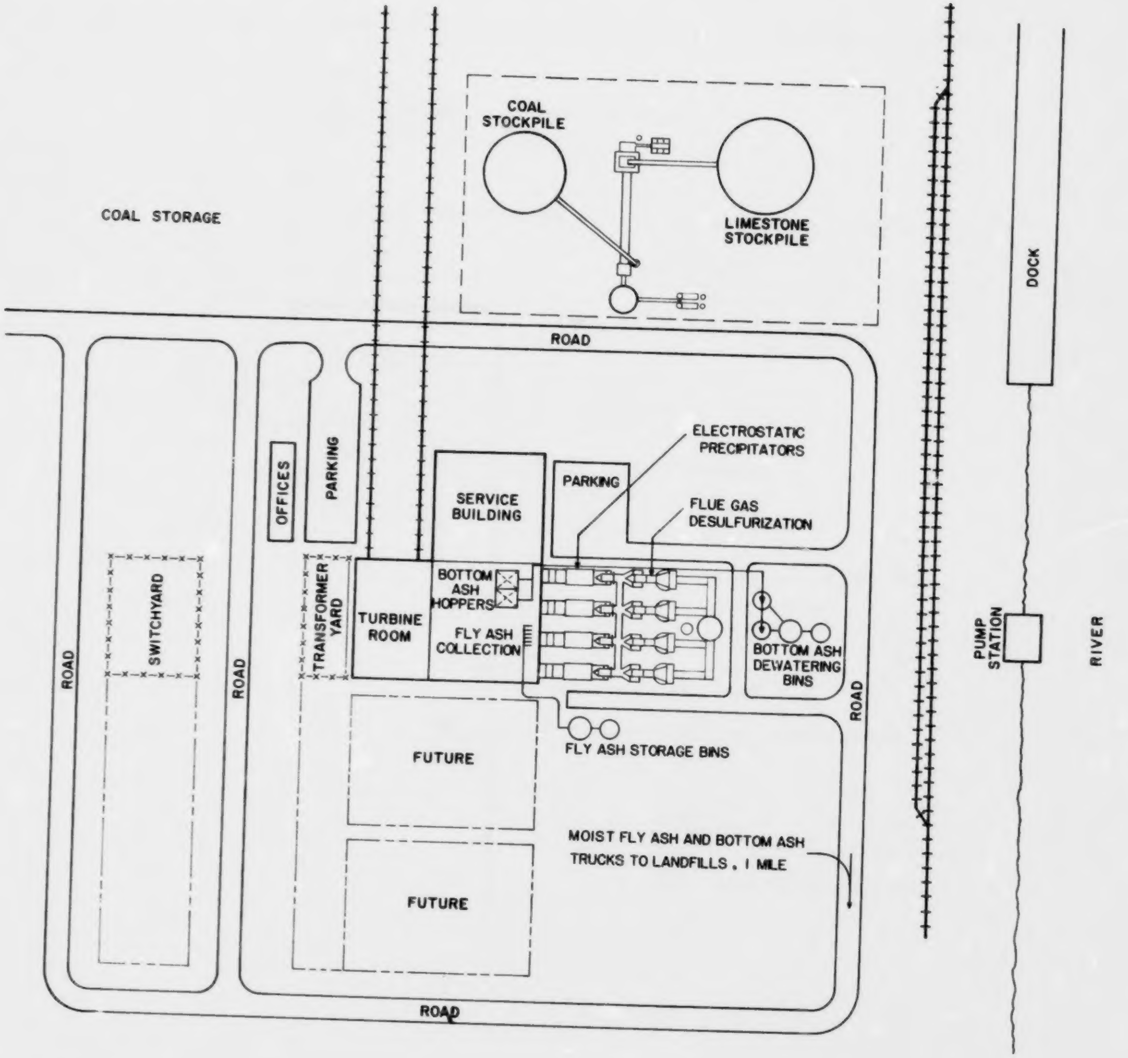

COAL STORAGE
COAL STOCKPILE
LIMESTONE STOCKPILE
DOCK
ROAD
ELECTROSTATIC PRECIPITATORS
FLUE GAS DESULFURIZATION
PARKING
SERVICE BUILDING
OFFICES
PARKING
SWITCHYARD
TRANSFORMER YARD
TURBINE ROOM
BOTTOM ASH HOPPERS
FLY ASH COLLECTION
BOTTOM ASH DEWATERING BINS
PUMP STATION
RIVER
ROAD
ROAD
ROAD
FLY ASH STORAGE BINS
FUTURE
FUTURE
MOIST FLY ASH AND BOTTOM ASH TRUCKS TO LANDFILLS, 1 MILE
ROAD

Figure 18. Plot plan. Base case 4, direct landfill of nonhardening ash.

TABLE 13. MATERIAL BALANCE

BASE CASE 4 - DIRECT LANDFILL OF NONHARDENING ASH

Stream No.		1	2	3	4	5
	Description	Coal ash to furnace	Ash to economizer	Ash collected from economizer	Air intake to economizer ash pneumatic system	Economizer ash in pneumatic system
1	Total stream, lb/hr	62,400	49,920	1,560	100	1,660
2						
3	Stream components, lb/hr					
4	Ash	62,400	49,920	1,560		1,560
5	Water					
6	Air				100	100
7						
8	ft^3/min, 60°F				22	
9	gal/min					
10	Percent solids					

Stream No.		6	7	8	9	10
	Description	Ash to air heater	Ash collected from air heater	Economizer-air heater ash in pneumatic system	Ash to ESP	Air intake to ESP ash pneumatic system
1	Total stream, lb/hr	48,360	1,560	3,220	46,800	1,390
2						
3	Stream components, lb/hr					
4	Ash	48,360	1,560	3,120	46,800	
5	Water					
6	Air			100		1,390
7						
8	ft^3/min, 60°F					303
9	gal/min					
10	Percent solids					

Steam No.		11	12	13	14	15
	Description	ESP ash in pneumatic system	Ash to FGD system	Ash in FGD waste	Ash to stack	Economizer-air heater ash from primary collector
1	Total stream, lb/hr	47,900	285	143	142	2,580
2						
3	Stream components, lb/hr					
4	Ash	46,510	285	143	142	2,580
5	Water					
6	Air	1,390				
7						
8	ft^3/min, 60°F					
9	gal/min					
10	Percent solids					

Stream No.		16	17	18	19	20
	Description	Economizer-air heater ash from secondary collector	Economizer-air heater ash from bag filter	Air from Economizer-air heater ash bag filter	Economizer-air heater ash from storage	Water to economizer-air heater ash moisturizer
1	Total stream, lb/hr	446	94	100	3,120	347
2						
3	Stream components, lb/hr					
4	Ash	446	94		3,120	0.4
5	Water					347
6	Air			100		
7						
8	ft^3/min, 60°F			22		
9	gal/min					0.7
10	Percent solids					

(continued)

TABLE 13 (continued)

Stream No.		21	22	23	24	25
	Description	Moisturized economizer-air heater ash to landfill	ESP ash from primary collector	ESP ash from secondary collector	ESP ash from bag filter	Air from fly ash bag filter
1	Total stream, lb/hr	3,468	38,470	6,650	1,390	1,390
2						
3	Stream components, lb/hr					
4	Ash	3,121	38,470	6,650	1,390	
5	Water	347				
6	Air					1,390
7						
8	ft^3/min, 60°F					303
9	gal/min					
10	Percent solids	90				

Stream No.		26	27	28	29	30
	Description	Air from mechanical exhauster	ESP ash utilization	ESP ash from storage	Water to ESP ash moisturizer	Moisturized ESP ash to to landfill
1	Total stream, lb/hr	1,490	0	46,510	5,160	51,670
2						
3	Stream components, lb/hr					
4	Ash			46,510	5	46,510
5	Water				5,160	5,160
6	Air	1,490				
7						
8	ft^3/min, 60°F	325				
9	gal/min				10	
10	Percent solids					90

Stream No.		31	32	33	34	35
	Description	Recycle water to to landfill	Fly ash landfill	Rainfall to fly ash landfill	Water from fly ash landfill to treatment	Water to bottom ash hopper
1	Total stream, lb/hr	4,710	59,800	90,840	90,890	50,950
2						
3	Stream components, lb/hr					
4	Ash	50	49,630		50	45
5	Water	4,660	10,170	90,840	90,840	50,900
6	Air					
7						
8	ft^3/min, 60°F					
9	gal/min	9		182	182	102
10	Percent solids		83			

Stream No.		36	37	38	39	40
	Description	Slurry to bottom ash pump	Underflow from settling tank	Water from dewatering bin to settling tank	Overflow water from settling tank	Underflow from water reservoir
1	Total stream, lb/hr	75,190	6,050	67,370	63,940	2,620
2						
3	Stream components, lb/hr					
4	Ash	12,540	540	600	70	10
5	Water	62,650	5,510	66,770	63,870	2,610
6	Air					
7						
8	ft^3/min, 60°F					
9	gal/min	138	12	134	128	5
10	Percent solids	16.7	9			

(continued)

TABLE 13 (continued)

	Stream No.	41	42	43	44	45
	Description	Bottom ash utilization	Dewatered bottom ash to landfill	Bottom ash landfill	Rainfall to bottom ash landfill	Runoff water from bottom ash landfill to treatment
1	Total stream, lb/hr	0	13,870	13,870	31,850	31,860
2						
3	Stream components, lb/hr					
4	Ash		12,480	12,480		5
5	Water		1,390	1,390	31,850	31,850
6	Air					
7						
8	ft^3/min, 60°F					
9	gal/min				64	64
10	Percent solids		90	90		

		46	47	48	49	50
	Description	Combined runoff water from landfill to treatment	Reagents for landfill water treatment	Treated landfill water to discharge	Reagents for water reservoir treatment	Overflow from water reservoir
1	Total stream, lb/hr	122,750	60	118,100	60	68,220
2						
3	Stream components, lb/hr					
4	Ash	55		10		60
5	Water	122,690		118,090		68,160
6	Air					
7	H_2SO_4		60		60	
8	ft^3/min, 60°F					
9	gal/min	245	0.06	236	0.06	136
10	Percent solids					

		51	52			
	Description	Makeup water	Water to bottom ash slurry			
1	Total stream, lb/hr	6,840	11,760			
2						
3	Stream components, lb/hr					
4	Ash		10			
5	Water	6,840	11,750			
6	Air					
7						
8	ft^3/min, 60°F					
9	gal/min	14	24			
10	Percent solids					

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

TABLE 14. EQUIPMENT LIST, DESCRIPTION, AND MATERIAL COST

BASE CASE 4 - DIRECT LANDFILL OF NONHARDENING ASH

Item (number): description	Material cost, delivered, 1982 k$
Area 1--Fly Ash Collection and Transfer	
1. *Economizer ash hoppers* (4): Inverted pyramid-type hopper, 15 ft long x 15 ft wide x 16 ft deep, thermally isolated design, constructed of 1/2-in. carbon steel plate	27
2. *Air heater ash hoppers* (4): Inverted pyramid-type hopper, 15 ft long x 7 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, insulated	21
3. *ESP ash hoppers* (32): Inverted pyramid-type hopper, 18 ft long x 12 ft wide x 16 ft deep, constructed of 1/2-in. carbon steel plate, heat traced and insulated	373
4. *Economizer-air heater ash collection and transfer system comprising* (1):	96
a. *Vacuum pneumatic conveying lines for economizer-air heater ash* (1): Pipelines and pipe fittings for vacuum pneumatic conveyance of ash, 5 ton/hr conveying capacity with 600-ft equivalent length system, 4-in. I.D. branch lines and 6-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard® or equivalent pipe fittings	
b. *Ash and air inlet valves* (8): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 4-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	
c. *Line segregating valves* (5): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 4-in. I.D. port, cast iron body, stainless steel slide gate	
d. *Vacuum breaker valves* (1): Vacuum breaker valve for control of vacuum in air line from bag filter, 6-in. I.D. port, cast iron body	

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
e. System control unit (1): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and mechanical exhauster; includes gauges for manual reading and override switches for manual operation	
5. Economizer-air heater ash separation system comprising (1):	26
a. Primary air-ash separator (1): Primary centrifugal separator with tangential air-ash inlet, cyclone-type vortex finding sleeve, and top vertical air outlet; two-gate, three-chamber ash removal and air lock provision cycled for continuous vacuum operation; 3.5 ft diameter x 12 ft high, 4.1 ton/hr capacity; carbon steel shell, Ni-Hard liners in high-velocity compartment	
b. Secondary air-ash separator (1): Secondary centrifugal separator similar to primary unit, 0.75 ton/hr capacity	
c. Air-ash bag filter (1): Bag filter for air-ash service at 150°F, 19-in. Hg vacuum, 200-ft^2 cloth area, cycled bag shaker and air-lock delivery to storage bin, 0.15 ton/hr capacity	
6. ESP ash collection and transfer system comprising (1):	160
a. Vacuum pneumatic conveying lines for ESP ash (1): Pipelines and pipe fittings for vacuum pneumatic conveyance of ash, 48 ton/hr conveying capacity with 600-ft equivalent length system, 6-in. I.D. branch lines and 10-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard or equivalent pipe fittings	
b. Ash and air inlet valves (32): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 6-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
c. Line segregating valves (5): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 6-in. I.D. port, cast iron body, stainless steel slide gate	
d. Vacuum breaker valve (1): Vacuum breaker valve for control of vacuum in air line from bag filter, 10-in. I.D. port, cast iron body	
e. System control unit (1): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and mechanical exhauster; includes gauges for manual reading and override switches for manual operation	
7. ESP ash separation system comprising (1):	52
a. Primary air-ash separator (1): Primary centrifugal separator with tangential air-ash inlet, cyclone-type vortex finding sleeve, and top vertical outlet; two-gate, three-chamber ash removal and air-lock provision cycled for continuous vacuum operation; 5 ft diameter x 17 ft high; 40 ton/hr capacity, carbon steel shell, Ni-Hard in high-velocity compartment	
b. Secondary air-ash separator (1): Secondary centrifugal separator similar to primary unit except 3.5 ft diameter x 12 ft high for 6.9 ton/hr capacity	
c. Air-ash bag filter (1): Bag filter for air-ash service at 150°F, 19-in. Hg vacuum, 1,200-ft^2 cloth area, cycled bag shaker and air-lock delivery to storage bin, 1.4 ton/hr capacity	
8. Mechanical exhausters for economizer-air heater and ESP ash collection and transfer systems (2 + 1 spare): Mechanical exhauster, two-impeller, straight-lobe type, 1,000 aft^3/min air at 19-in. Hg vacuum and 150°F, 8-in. I.D. inlet, connected to common vacuum plenum, equipped with silencer and inline prefilter, 100 hp	79
Total, Area 1	834

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 2--Fly Ash Conveyance to Disposal Site	
1. Economizer-air heater ash storage bin (1): Economizer-air heater ash storage bin, 16 ft diameter x 18 ft high, 3,600 ft volume, with bin-air fluidizing system and vent filter, elevated construction for 22-ft railroad clearance, carbon steel plate, 5 hp	211
2. ESP ash storage bin (1): ESP ash storage bin 38 ft diameter x 50 ft high, 57,000 ft volume, with bin-air fluidizing system and vent filter, elevated construction for 22-ft railroad clearance, carbon steel plate, 10 hp	468
3. Moisturizers for economizer-air heater and ESP ash from storage bins (2): Continuous unloader and mixer for moisturizing to 90% solids, includes rotary star feeder to control flow from storage bin, double-flight screw conveyor, 30-in.-diameter drum, 50 ton/hr capacity, 5 hp	50
4. Trucks for hauling economizer-air heater ash and ESP ash from storage bins to fly ash landfill (2 + 1 spare): Tandem-axle 4 rear-wheel-drive dump truck with ash haul body, air heater ash 20-yd^3 capacity, 44,000-lb and ESP ash from suspension, 6 forward-speed storage bins to manual transmission, 237-hp fly ash landfill diesel engine (costed 80% in Area 2 and 20% in Area 6)	211
Total, Area 2	940
Area 3--Fly Ash Disposal Site	
1. Fly ash landfill (1): Fly ash landfill, 1,809 ft square with 1-ft-thick clay liner, volume of 3,367,000 yd^3, constructed in one 20-ft lift with edge sloped upward at 1-vertical to 2-horizontal (27°), edges and top covered as filled with 1/2-ft-thick layer of clay and 1-1/2-ft-thick layer of topsoil, 20-ft finished height at edge with top sloped upward to center of landfill at 1-vertical to 29-horizontal (2°), landfill surrounded by runoff and leachate collection ditch 24 ft wide x 2.5 ft deep with 1-ft-thick clay liner; ditch drains to common 284-ft-square catchment basin with 1-ft-thick clay liner; site includes 363-ft-square common topsoil	(1,946)[a]

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
storage area, office trailer with sanitary facilities, equipment storage area, 24-ft-wide access roads, on-site water supply well and three peripheral monitoring wells; landfill periphery is enclosed by 6-ft-high security fence	
2. Dozers for moving ash and earth at landfill (2): D4E Caterpillar or equivalent track-type with 10-ft-long U-shaped blade, 75-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	118
3. Compactor for ash at landfill (1): Vibratory sheepsfoot compactor, self propelled, Raygo 420 C or equivalent (costed 80% in Area 3 and 20% in Area 7)	70
4. Tank truck for dust control at landfill (1): Tandem axle, 4 rear-wheel-drive tank truck with spray nozzle boom attachment, and pumping system, 2,000-gal fiberglass tank, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	33
5. Front-end loader for stripping and restoring topsoil (1): 950 Caterpillar or equivalent, wheeled, with 3-yd bucket, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	93
6. Service truck for fuel, lubricants, and field service (1): Service truck with 500-gal cargo tank for diesel fuel and cargo space for lubricants and other field service items (costed 80% in Area 3 and 20% in Area 7)	20
Total, Area 3	334
Area 4--Fly Ash Water Treatment and Recycle of Water (Costed 80% in Area 4 and 20% in Area 8)	
1. Sulfuric acid storage tank for pH control of water to discharge (1): Cylindrical steel tank, 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
2. Metering pump for sulfuric acid (1 + 1 spare): Positive displacement metering pump, 0.01 to 1 gpm, 0 psig, with flow rate controlled by a pH controller, Carpenter 20® alloy or similar corrosion resistance to 93% sulfuric acid; 0.25-hp	2
3. Agitator for mixing of treated water (1): Agitator with 24-in.-diameter nickel-chromium blade; 5 hp	3
4. Pump for solids slurry from water treatment (1 + 1 spare): Centrifugal pump, 10 gpm, 20 psig, carbon steel body and impeller, 0.5 hp	1
5. Automatic sampler for water to discharge (1): Automatic sampler with sampler size controlled by flow rate, refrigerated storage of composite sample; all-weather housing	4
Total, Area 4	12
Area 5--Bottom Ash Collection and Transfer	
1. Water supply pumps for bottom ash hopper and slurry (1 + 1 spare): Centrifugal pump, 550 gpm, 250-ft head, carbon steel body and impeller, 60 hp	34
2. Bottom ash hopper assembly (1): Double-V hopper with 3,320-ft^3 capacity for 12-hr ash containment, supported independently of furnace-boiler and mated to furnace through a water seal trough spanning the furnace seal plate, hopper body of 3/8-in.-thick carbon steel plate, hopper lined with monolithic refractory 9 in. thick in upper section and 6 in. thick in lower section, stainless steel seal trough and overflow weirs, assembly includes poke doors, lighted observation windows, access doors, and hydraulically operated ash exit doors; each V-section of hopper includes two hopper-type, double-roll grinders with cast iron body and 10-in.-diameter x 2-ft-long manganese steel rolls; 60 hp	352
Total, Area 5	386

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 6--Bottom Ash Conveyance to Disposal Site	
1. Slurry pumps for pipeline conveyance (1 + 1 spare): Centrifugal slurry pumps, 550 gpm, 150-ft head, Ni-Hard liner and impeller, 50-hp motor	52
2. Shutoff and crossover valves (10): Air-operated gate valve, 8-in. I.D. port, Ni-Hard	23
3. One-eighth mile basalt-lined slurry pipeline to dewatering bins, normal use (1): Pipeline comprising 37 18-ft-long sections of flanged, basalt-lined steel pipe, 8-in. I.D. and 4 basalt-lined elbows or bends, 8-in. I.D.	(46)[a]
4. Spare slurry pipeline to dewatering bins (1): Pipeline comprising 17 40-ft-long sections of flanged steel pipe, 8-in. I.D., schedule 80 carbon steel and 4 hardened elbows or bends, 8-in. I.D.	(12)[a]
5. Dewatering bins for bottom ash slurry (2): Conical-bottom dewatering bin, 25-ft-diameter x 19-ft-high cylindrical section, 19-ft-high cone, 11,100 ft^3, stainless steel floating decanter and movable drain pipe, stationary decanters in conical section, erected for 22-ft railroad clearance, carbon steel bin, stainless steel decanter drum	430
6. Trucks for hauling moist bottom ash from dewatering bins to bottom ash landfill (2 + 1 spare): Same trucks as in Area 2, Item 4 (costed 20% in Area 6 and 80% in Area 2)	53
Total, Area 6	558
Area 7--Bottom Ash Disposal Site	
1. Bottom ash landfill (1): Bottom ash landfill, 1,011 ft square with 1-ft-thick clay liner, volume of 847,000 yd^3, constructed in one 20-ft lift with edge sloped upward at 1-vertical to 2-horizontal (27°), edges and top covered as filled with 1/2-ft-thick layer of clay and 1-1/2-ft-thick layer of topsoil, 20-ft finished height at	(487)[a]

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
edge with top sloped upward to center of landfill at 1-vertical to 29-horizontal (2°), landfill surrounded by runoff and leachate collection ditch 24 ft wide x 2.5 ft deep with 1-ft-thick clay liner; ditch drains to common 284-ft-square catchment basin with 1-ft-thick clay liner; site includes 363-ft-square common topsoil storage area, office trailer with sanitary facilities, equipment storage area, 24-ft-wide access roads, onsite water supply well and 2 peripheral monitoring wells; landfill periphery is enclosed by 6-ft-high security fence	
2. Dozers for moving ash and earth at landfill (2): Same dozers as in Area 3, Item 2 (costed 20% in Area 7 and 80% in Area 3)	30
3. Compactor for ash at landfill (1): Same compactor as in Area 3, Item 3 (costed 20% in Area 7 and 80% in Area 3)	18
4. Tank truck for dust control at landfill (1): Same trucks as in Area 3, 8 Item 4 (costed 20% in Area 7 and 80% in Area 3)	8
5. Front-end loader for stripping and restoring topsoil (1): Same loader as in Area 3, Item 5 (costed 20% in Area 7 and 80% in Area 3)	23
6. Service truck for fuel, lubricants, and field service (1): Same service truck as in Area 3, 5 Item 7 (costed 20% in Area 7 and 80% in Area 3)	5
Total, Area 7	84
Area 8--Bottom Ash Water Treatment and Recycle of Water	
1. Settling tank for clarifying water (1): Settling tank, 50 ft diameter x 15 ft deep, 220,000 gal, carbon steel	73
2. Water reservoir for bottom ash dewatering system (1): Water reservoir, 40 ft diameter x 16 ft deep, 150,000 gal, carbon steel	52

(continued)

TABLE 14 (continued)

Item (number): description	Material cost, delivered, 1982 k$
3. Recycle pump for underflow solids from settling tank and water reservoir (1): Centrifugal pump, 100 gpm, 100-ft head, carbon steel body and impeller, 5 hp	3
4. Sulfuric acid storage tank for pH control of return water from water reservoir (1): Cylindrical steel tank, 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2
5. Metering pump for sulfuric acid to return water (1): Positive displacement metering pump 0.01 to 1 gpm, 0 psig, Carpenter 20 alloy or similar corrosion resistance to 93% sulfuric acid; 0.25-hp, flow rate controlled by a pH controller	2
6. Sulfuric acid storage tank for pH control of water to discharge (1): Same tank as in Area 4, Item 1 (costed 20% in Area 8 and 80% in Area 4)	0.5
7. Metering pump for sulfuric acid to discharge water (1 + 1 spare): Same pump as in Area 4, Item 2 (costed 20% in Area 8 and 80% in Area 4)	0.5
8. Agitator for mixing of treated water (1): Same agitator as in Area 4, Item 3 (costed 20% in Area 8 and 80% in Area 4)	0.75
9. Pump for solids slurry from water treatment (1 + 1 spare): Same pump as in Area 4, Item 4 (costed 20% in Area 8 and 80% in Area 4)	0.25
10. Automatic sampler for water to discharge (1): Same sampler as in Area 4, Item 5 (costed 20% in Area 8 and 80% in Area 4)	1
Total, Area 8	135
Total, Base Case 4	3,283

a. Costs shown in parentheses are informational and are not included in area or base case totals for equipment material costs.

Ash is removed from the silos through moisturizers that blend water with the ash to control dusting. Each moisturizer consists of an inclined rotating drum containing a screw conveyor and water spray nozzles. Fly ash is fed from the silos through a rotary feeder. It is blended with 10% water in the moisturizer by the mixing action of the rotating drum and the screw conveyor, which moves it upslope to the discharge. The moistened ash falls directly from the moisturizer into a truck.

Bottom Ash Collection

Bottom ash is sluiced from the bottom ash hoppers in a system identical to that of base case 1. Instead of being pumped to a pond, however, it is pumped 660 feet to one of two dewatering bins. Because of the short distance the ash content of the slurry is 16.7% instead of the 7.7% used in the previous base cases.

The dewatering bins are conical-bottom steel vessels 25 feet in diameter by 38 feet high with an 83,000 gallon (11,100 ft^3) volume and a 10-hour capacity. The bins are elevated for direct loading into trucks or rail cars. The associated water recycling system consists of a 220,000 gallon settling tank and a 150,000 gallon water reservoir. A sulfuric acid water treatment system is also included.

At the beginning of the ash removal cycle the dewatering bin that is to receive the ash is partially full of water. The ash is sluiced to the dewatering bin using water from the bottom ash hopper and the reservoir tank while overflow water from the dewatering bin flows through the settling tank and back to the reservoir tank. Bottoms from the settling tank, which contain fines and sludge, are pumped back to the dewatering bin. At the end of the ash removal cycle the dewatering bin is drained to the settling tank and overflowed to the reservoir tank. Ash is allowed to drain to a water content of 10% and is dumped to trucks and at the same time the alternate dewatering bin is being partially filled from the reservoir tank. Makeup water and sulfuric acid for pH adjustment are added to the reservoir tank as necessary. The ash slurry rate to the dewatering bin is 550 gal/min while the system is operating and averages 138 gpm over a 24-hour period. After dewatering, each dewatering bin has an ash capacity of about 40 hours of boiler operation.

Ash Transportation

Moistened fly ash from the moisturizers on the fly ash silos and bottom ash from the dewatering bins are dumped directly into trucks and hauled to the disposal site. Two 44,000 lb, 20 yd^3, ash-haul-body trucks are used for total ash haulage and they are operated two shifts/day during the power plant operating year.

Landfill

Fly ash and bottom ash are trucked to separate contiguous landfills on a site one mile from the power plant. The landfill has a 30-year capacity. The disposal site design is described in the premises. The design and operation is similar to the base case 3 landfill except for the segregation of ash by type. The disposal site occupies 142 acres, 75 acres of which is a fly ash landfill of 3.4 million yd^3 and 24 acres of which is a bottom ash landfill of 0.8 million yd^3. Both landfills are stripped, prepared, filled, and covered in successive sections using topsoil from each section stripped to cover the previous section. A 1-foot clay liner, a 2-foot porous base of bottom ash for the fly ash landfill, and a catchment basin identical in function to base case 3 are provided.

The ash is built up in successive compacted layers to a center of 50 feet for the fly ash landfill and 36 feet for the bottom ash landfill. The side slope is 1 vertical to 2 horizontal and there is slight slope of the top upward to the center. A compacted dry bulk density of 90 lb/ft^3 and a 17% moisture content are used for the fly ash landfill while the bottom ash landfill has 10% moisture. At the design height the ash is covered with 6 inches of clay and 18 inches of topsoil and revegetated.

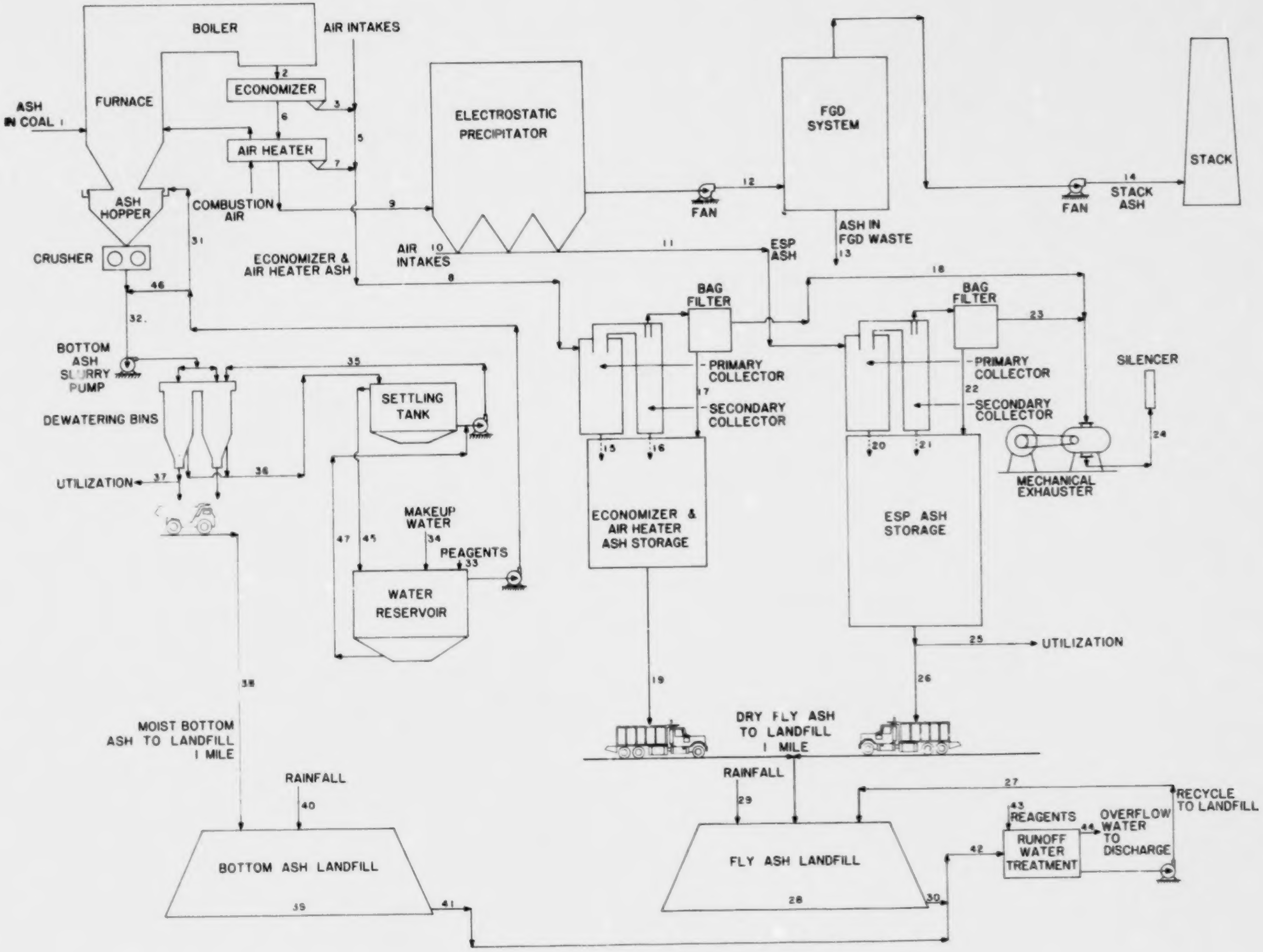
Provisions for monitoring wells, catchment basin water treatment, offices and equipment facilities, roads, and topsoil storage are also included. Two dozers, a front-end loader, a compactor, and a watering truck are provided for operation of the site.

BASE CASE 5 - DIRECT LANDFILLING OF SELF-HARDENING ASH

Base case 5 represents an increasingly common situation in which a high-calcium coal is used. These coals are typically western coals characterized by a lower sulfur and ash content and a lower heating value than typical eastern coals, as well as a higher alkali and alkali earth metal content. The use of the low-sulfur western coal described in the premises results in the production of 24% less ash than that produced using the high-sulfur eastern coal. It also results in an ash containing 10% calcium instead of the 2% with the eastern coal. The self-hardening properties of such high-calcium fly ashes can create disposal problems if the ash is wetted before final placement and compaction at the disposal site. From some coals, the ash may harden sufficiently to set up in bins, lines, and trucks and it may be difficult to compact. The inherent increase in shear strength and impermeability of self-hardening ash may also be lost if the reactions are allowed to start before placement and compaction. Bottom ash, which is composed of larger, less-reactive particles, does not normally present such problems.

The handling and disposal methods of base case 5 are designed to keep the fly ash dry until immediately before it is placed in the landfill. The flow diagram, disposal site plan, and plot plan are shown in Figures 19, 20, and 21. The material balance and equipment list are shown in Tables 15 and 16.

Economizer and air heater fly ash and ESP fly ash are collected separately in storage bins using a pneumatic vacuum system powered by mechanical exhausters. Bottom ash is sluiced to dewatering bins using recycled water. The ashes are placed in separate landfills on the same disposal site situated one mile from the power plant. The fly ash is transported dry in covered dump trucks. It is blended with water by truck-mounted moisturizers as it is dumped. The bottom ash is transported in regular dump trucks. The landfill design and operation are the same as those of base case 4.


BOILER
AIR INTAKES
ASH IN COAL 1
FURNACE
ECONOMIZER
AIR HEATER
ASH HOPPER
COMBUSTION AIR
CRUSHER
ECONOMIZER & AIR HEATER ASH
ELECTROSTATIC PRECIPITATOR
AIR INTAKES 10
FAN
FGD SYSTEM
ASH IN FGD WASTE 13
ESP ASH
FAN
STACK ASH 14
STACK
BAG FILTER
PRIMARY COLLECTOR
SECONDARY COLLECTOR
ECONOMIZER & AIR HEATER ASH STORAGE
BAG FILTER
PRIMARY COLLECTOR
SECONDARY COLLECTOR
ESP ASH STORAGE
SILENCER
MECHANICAL EXHAUSTER
UTILIZATION
BOTTOM ASH SLURRY PUMP
DEWATERING BINS
UTILIZATION
SETTLING TANK
MAKEUP WATER
PEAGENTS
WATER RESERVOIR
MOIST BOTTOM ASH TO LANDFILL 1 MILE
DRY FLY ASH TO LANDFILL 1 MILE
RAINFALL
RAINFALL
BOTTOM ASH LANDFILL
FLY ASH LANDFILL
REAGENTS
RUNOFF WATER TREATMENT
OVERFLOW WATER TO DISCHARGE
RECYCLE TO LANDFILL
2
3
5
6
7
8
9
11
12
15
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17
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46
47

Figure 19. Flow diagram. Base case 5, direct landfill of self-hardening ash.

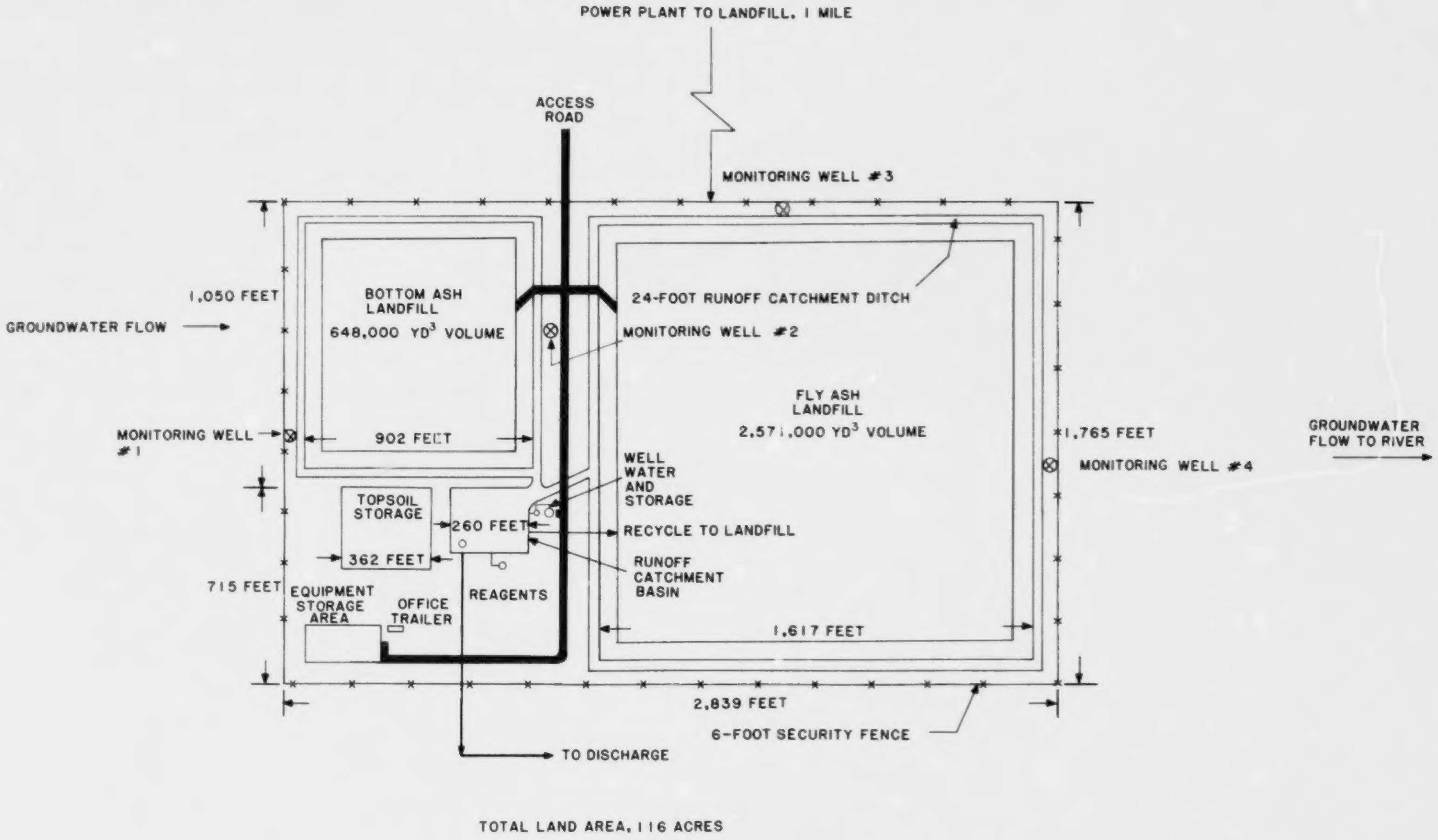
POWER PLANT TO LANDFILL. 1 MILE
ACCESS ROAD
MONITORING WELL #3
1,050 FEET
BOTTOM ASH LANDFILL
648,000 YD³ VOLUME
24-FOOT RUNOFF CATCHMENT DITCH
GROUNDWATER FLOW
MONITORING WELL #2
FLY ASH LANDFILL
2,571,000 YD³ VOLUME
MONITORING WELL #1
902 FEET
1,765 FEET
GROUNDWATER FLOW TO RIVER
MONITORING WELL #4
WELL WATER AND STORAGE
TOPSOIL STORAGE
260 FEET
RECYCLE TO LANDFILL
362 FEET
RUNOFF CATCHMENT BASIN
715 FEET
EQUIPMENT STORAGE AREA
OFFICE TRAILER
REAGENTS
1,617 FEET
2,839 FEET
6-FOOT SECURITY FENCE
TO DISCHARGE
TOTAL LAND AREA, 116 ACRES

Figure 20. Disposal site. Base case 5, direct landfill of self-hardening ash.

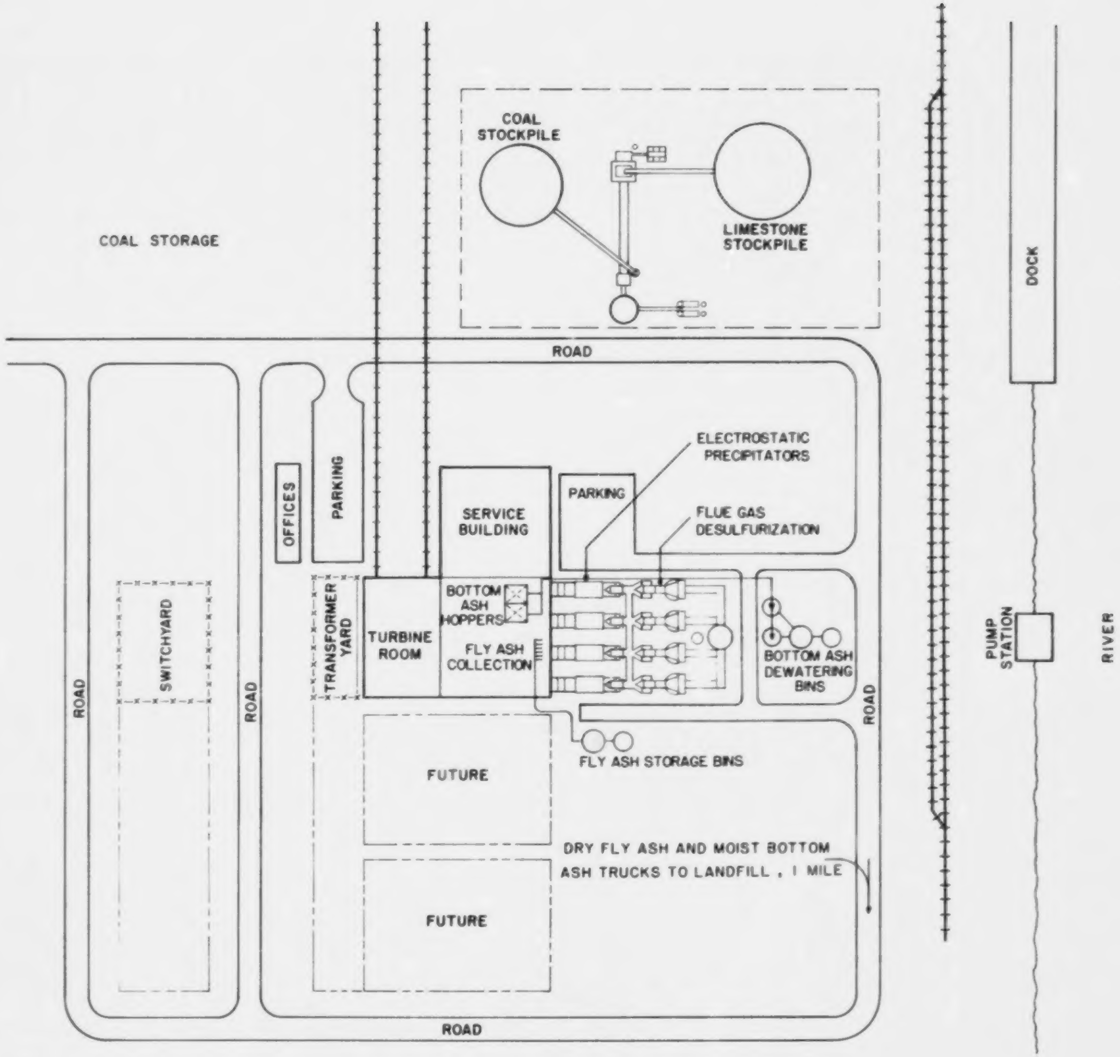
COAL STORAGE
COAL STOCKPILE
LIMESTONE STOCKPILE
DOCK
ROAD
OFFICES
PARKING
SERVICE BUILDING
PARKING
ELECTROSTATIC PRECIPITATORS
FLUE GAS DESULFURIZATION
SWITCHYARD
TRANSFORMER YARD
TURBINE ROOM
BOTTOM ASH HOPPERS
FLY ASH COLLECTION
BOTTOM ASH DEWATERING BINS
PUMP STATION
RIVER
ROAD
ROAD
ROAD
FLY ASH STORAGE BINS
FUTURE
FUTURE
DRY FLY ASH AND MOIST BOTTOM ASH TRUCKS TO LANDFILL , 1 MILE
ROAD

Figure 21. Plot plan. Base case 5, direct landfill of self-hardening ash.

TABLE 15. MATERIAL BALANCE

BASE CASE 5 - DIRECT LANDFILL OF SELF-HARDENING ASH

Stream No.		1	2	3	4	5
Description		Coal ash to furnace	Ash to economizer	Ash collected from economizer	Air intake to economizer ash pneumatic system	Economizer ash in pneumatic system
1	Total stream, lb/hr	47,730	38,180	1,190	71	1,260
2						
3	Stream components, lb/hr					
4	Ash	47,730	38,180	1,190		1,190
5	Water					
6	Air				71	71
7						
8	$Ft^3/min, 60^oF$				16	
9	Gal/min					
10	Percent Solids					

Stream No.		6	7	8	9	10
Description		Ash to air heater	Ash collected from air heater	Economizer-air heater ash in pneumatic system	Ash to ESP	Air intake to ESP ash pneumatic system
1	Total stream, lb/hr	36,990	1,190	2,450	35,800	1,066
2						
3	Stream components, lb/hr					
4	Ash	36,990	1,190	2,380	35,800	
5	Water					
6	Air			71		1,066
7						
8	$Ft^3/min, 60^oF$					232
9	Gal/min					
10	Percent solids					

Stream No.		11	12	13	14	15
Description		ESP ash in pneumatic system	Ash to FGD system	Ash in FGD waste	Ash to stack	Economizer-air heater ash from primary collector
1	Total stream, lb/hr	36,580	285	143	142	1,970
2						
3	Stream components, lb/hr					
4	Ash	35,510	285	143	142	1,970
5	Water					
6	Air	1,066				
7						
8	$Ft^3/min, 60^oF$					
9	Gal/min					
10	Percent solids					

Stream No.		16	17	18	19	20
Description		Economizer-air heater ash from secondary collector	Economizer air heater ash from bag filter	Air from economizer-ash heater ash bag filter	Economizer air heater ash from storage	ESP ash from primary collector
1	Total stream, lb/hr	340	70	71	2,380	29,370
2						
3	Stream components, lb/hr					
4	Ash	340	70		2,380	29,370
5	Water					
6	Air			71		
7						
8	$Ft^3/min, 60^oF$			16		
9	Gal/min					
10	Percent solids					

(continued)

TABLE 15 (continued)

	Stream No.	21	22	23	24	25
	Description	ESP ash from secondary collector	ESP ash from bag filter	Air from ESP ash bag filter	Air from mechanical exhauster	ESP ash utilization
1	Total stream, lb/hr	5,080	1,060	1,066	1,137	0
2						
3	Stream components, lb/hr					
4	Ash	5,080	1,060			
5	Water					
6	Air			1,066	1,137	
7						
8	Ft^3/min, 60°F			232	248	
9	Gal/min					
10	Percent solids					

	Stream No.	26	27	28	29	30
	Description	ESP ash from storage	Recycle water to onsite moisturizer	Fly ash landfill	Rainfall to fly ash landfill	Runoff water from fly ash landfill to treatment
1	Total stream, lb/hr	35,510	7,810	45,660	65,760	65,800
2						
3	Stream components, lb/hr					
4	Ash	35,510	40	37,890		40
5	Water		7,770	7,770	65,760	65,760
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min		16		132	132
10	Percent solids			83		

	Stream No.	31	32	33	34	35
	Description	Water to bottom ash hopper	Slurry to bottom ash pump	Reagents for water reservoir treatment	Makeup water	Underflow from settling tank
1	Total stream, lb/hr	38,990	57,600	420	640	3,600
2						
3	Stream components, lb/hr					
4	Ash	40	9,600			450
5	Water	38,950	48,000		640	3,150
6	Air					
7	H_2SO_4			420		
8	Ft^3/min, 60°F					
9	Gal/min	78	106	0.4	1.3	6.8
10	Percent solids		16.7			

	Stream No.	36	37	38	39	40
	Description	Water from dewatering bin to settling tank	Bottom ash utilization	Dewatered bottom ash to landfill	Bottom ash landfill	Rainfall to bottom ash landfill
1	Total stream, lb/hr	50,590	0	10,610	10,600	21,380
2						
3	Stream components, lb/hr					
4	Ash	500		9,550	9,540	
5	Water	50,090		1,060	1,060	21,380
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min	101				43
10	Percent solids	1		90	90	

(continued)

TABLE 15 (continued)

	Stream No.	41	42	43	44	45
	Description	Runoff water from bottom ash landfill to treatment	Combined runoff water from landfill to treatment	Reagents for landfill water treatment	Treated landfill water to discharge	Overflow water from settling tank
1	Total stream, lb/hr	21,390	87,190	60	79,440	48,490
2						
3	Stream components, lb/hr					
4	Ash	10	50		10	60
5	Water	21,380	87,140		79,430	48,430
6	Air					
7	H_2SO_4			60		
8	Ft^3/min, 60°F					
9	Gal/min	43	174	0.06	159	97
10	Percent solids					

	Stream No.	46	47			
	Description	Water to bottom ash slurry	Underflow from water reservoir			
1	Total stream, lb/hr	9,060	1,500			
2						
3	Stream components, lb/hr					
4	Ash	10	10			
5	Water	9,050	1,490			
6	Air					
7						
8	Ft^3/min, 60°F					
9	Gal/min	18	3			
10	Percent solids					

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

TABLE 16. EQUIPMENT LIST, DESCRIPTION, AND MATERIAL COST

BASE CASE 5 - DIRECT LANDFILL OF SELF-HARDENING ASH

Item (number): description	Material cost, delivered, 1982 k$
Area 1--Fly Ash Collection and Transfer	
1. Economizer ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 15 ft wide x 13 ft deep, thermally isolated design, constructed of 1/2-in. carbon steel plate	22
2. Air heater ash hoppers (4): Inverted pyramid-type hopper, 15 ft long x 7 ft wide x 13 ft deep, constructed of 1/2-in. carbon steel plate, insulated	17
3. ESP ash hoppers (32): Inverted pyramid-type hopper, 18 ft long x 12 ft wide x 13 ft deep, constructed of 1/2-in. carbon steel plate, heat traced and insulated	317
4. Economizer-air heater ash collection and transfer system comprising (1):	96
a. Vacuum pneumatic conveying lines for economizer-air heater ash (1): Pipelines and pipe fittings for vacuum pneumatic conveyance of ash, 5 ton/hr conveying capacity with 600-ft equivalent length system, 4-in. I.D. branch lines and 5-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard® or equivalent pipe fittings	
b. Ash and air inlet valves (8): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 4-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	
c. Line segregating valves (5): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 4-in. I.D. port, cast iron body, stainless steel slide gate	
d. Vacuum breaker valves (1): Vacuum breaker valve for control of vacuum in air line from bag filter, 5-in. I.D. port, cast iron body	

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
e. System control unit (1): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and mechanical exhauster; includes gauges for manual reading and override switches for manual operation	
5. Economizer-air heater ash separation system comprising (1):	21
a. Primary air-ash separator (1): Primary centrifugal separator with tangential air-ash inlet, cyclone-type vortex finding sleeve, and top vertical air outlet; two-gate, three-chamber ash removal and air lock provision cycled for continuous vacuum operation; 3 ft diameter x 10 ft high, 3.1 ton/hr capacity; carbon steel shell, Ni-Hard liners in high-velocity compartment	
b. Secondary air-ash separator (1): Secondary centrifugal separator similar to primary unit, 0.6 ton/hr capacity	
c. Air-ash bag filter (1): Bag filter for air-ash service at 150°F, 19-in. Hg vacuum, 150-ft^2 cloth area, cycled bag shaker and air-lock delivery to storage bin, 0.1 ton/hr capacity	
6. ESP ash collection and transfer system comprising (1):	114
a. Vacuum pneumatic conveying lines for ESP ash (1): Pipelines and pipe fittings for vacuum pneumatic conveyance of ash, 36 ton/hr conveying capacity with 600-ft equivalent length system, 5-in. I.D. branch lines and 8-in. I.D. main lines, nickel-chromium cast iron pipe with Ni-Hard or equivalent pipe fittings	
b. Ash and air inlet valves (32): Self-feeding materials handling valve, electrically actuated, air operated, 12-in. I.D. ash inlet, 6-in. I.D. ash outlet, cast iron body, stainless steel slide gate; each assembly includes two spring-loaded, air-inlet check valves with cast iron bodies	

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
c. Line segregating valves (5): Segregating slide valve, electrically actuated, air operated for on-off control of each branch conveying line, 5-in. I.D. port, cast iron body, stainless steel slide gate	
d. Vacuum breaker valves (1): Vacuum breaker valve for control of vacuum in air line from bag filter, 8-in. I.D. port, cast iron body	
e. System control unit (1): Automatic sequence control unit to control the programmed operation of materials handling valves, line segregating valves, and mechanical exhauster; includes gauges for manual reading and override switches for manual operation	
7. ESP ash separation system comprising (1):	42
a. Primary air-ash separator (1): Primary centrifugal separator with tangential air-ash inlet, cyclone-type vortex finding sleeve, and top vertical outlet; two-gate, three-chamber ash removal and airlock provision cycled for continuous vacuum operation; 4.5 ft diameter x 14 ft high; 30 ton/hr capacity, carbon steel shell, Ni-Hard liners in high-velocity compartment	
b. Secondary air-ash separator (1): Secondary centrifugal separator similar to primary unit except 3 ft diameter x 10 ft high for 5 ton/hr capacity	
c. Air-ash bag filter (1): Bag filter for air-ash service at 150°F, 19-in. Hg vacuum, 900-ft^2 cloth area, cycled bag shaker and air-lock delivery to storage bin, 1 ton/hr capacity	
8. Mechanical exhausters for economizer-air heater and ESP ash collection and transfer systems (2 + 1 spare): Mechanical exhauster, two-impeller, straight-lobe type, 760 aft^3/min air at 19-in. Hg vacuum and 150°F, 8-in. I.D. inlet, connected to common vacuum plenum, equipped with silencer and inline prefilter, 75 hp	64
Total, Area 1	693

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 2--Fly Ash Conveyance to Disposal Site	
1. Economizer-air heater ash storage bin (1): Economizer-air heater ash storage bin, 14 ft diameter x 16 ft high, 2,460-ft^3 volume, with bin-air fluidizing system and, vent filter, elevated construction for 22-ft railroad clearance, carbon steel plate, 5 hp	206
2. ESP ash storage bin (1): ESP ash storage bin, 32 ft diameter x 44 ft high, carbon steel construction, 35,000-ft^3 volume, with bin-air fluidizing system and vent filter, elevated construction for 22-ft railroad clearance, carbon steel plate, 10 hp	379
3. Trucks for hauling economizer-air heater ash and ESP ash from storage bins to fly ash landfill (2 + 1 spare): Tandem-axle, 4 rear-wheel-drive tank truck, 15 yd^3 capacity, with covered ash haul body, tailgate skirted and equipped with water spray nozzles for dust control, 400-gal water tank, water pump capacity of 40 gpm at 40 psig, water pump driven by power takeoff, 44,000-lb suspension, 6-forward speed manual transmission 237-hp diesel engine	248
Total, Area 2	833
Area 3--Fly Ash Disposal Site	
1. Fly ash landfill (1): Fly ash landfill, 1,617 ft square with 1-ft-thick clay liner, volume of 2,571,000 yd^3, constructed in one 20-ft lift with edge sloped upward at 1-vertical to 2-horizontal (27°), edges and top covered as filled with 1/2-ft-thick layer of clay and 1-1/2-ft-thick layer of topsoil, 20-ft finished height at edge with top sloped upward to center of landfill at 1-vertical to 29-horizontal (2°), landfill surrounded by runoff and leachate collection ditch 24 ft wide x 2.5 ft deep with 1-ft-thick clay liner; ditch drains to common 260-ft-square catchment basin with 1-ft-thick clay liner; site includes 362-ft-square common topsoil storage area, office trailer with sanitary facilities, equipment storage area, 24-ft-wide access	(1,630)[a]

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
roads, onsite water supply well and three peripheral monitoring wells; landfill periphery is enclosed by 6-ft-high security fence	
2. Dozer for moving ash and earth at landfill (1): D4E Caterpillar or equivalent track-type with 10-ft-long U-shaped blade, 75-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	59
3. Compactor for ash at landfill (1): Vibratory sheepsfoot compactor, self-propelled, Raygo 420 C or equivalent (costed 80% in Area 3 and 20% in Area 7)	70
4. Tank trucks for dust control at landfill (2): Tandem-axle, 4 rear-wheel-drive tank truck with spray nozzle boom attachment, and pumping system, 2,000-gal fiberglass tank, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	66
5. Front-end loader for stripping and restoring topsoil (1): 950 Caterpillar or equivalent with 3-yd^3 bucket, 130-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	93
6. Dozer for ash handling (1): DE Caterpillar or equivalent track-type with 62-hp diesel engine (costed 80% in Area 3 and 20% in Area 7)	42
7. Service truck for fuel, lubricants, and field service (1): Service truck with 500-gal cargo tank for diesel fuel and cargo space for lubricants and other field service items (costed 80% in Area 3 and 20% in Area 7)	20
Total, Area 3	350
Area 4--Fly Ash Water Treatment and Recycle of Water (Costed 80% in Area 4 and 20% in Area 8)	
1. Sulfuric acid storage tank for pH control of water to discharge (1): Cylindrical steel tank 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
2. Metering pump for sulfuric acid (1 + 1 spare): Positive displacement metering pump 0.01 to 1 gpm, 0 psig, with flow rate controlled by a pH controller, Carpenter 20® alloy or similar corrosion resistance to 93% sulfuric acid; 0.25-hp	2
3. Agitator for mixing of treated water (1): Agitator with 24-in.-diameter nickel-chromium blade; 5 hp	3
4. Pump for solids (1 + 1 spare): Centrifugal pump, 20 gpm, 20 psig, carbon steel body and impeller, 0.5 hp	1
5. Automatic sampler for water to discharge (1): Automatic sampler with sample size controlled by flow rate, refrigerated storage of composite sample; all-weather housing	4
Total, Area 4	12
Area 5--Bottom Ash Collection and Transfer	
1. Water supply pumps for bottom ash hopper and slurry (1 + 1 spare): Centrifugal pump, 385 gpm, 250-ft head, carbon steel body and impeller, 50 hp	29
2. Bottom ash hopper assembly (1): Double-V hopper with 2,540-ft capacity for 12-hr ash containment, supported independently of furnace-boiler and mated to furnace through a water seal trough spanning the furnace seal plate, hopper body of 3/8-in.-thick carbon steel plate, hopper lined with monolithic refractory 9 in. thick in upper section and 6 in. thick in lower section, stainless steel seal trough and overflow weirs, assembly includes poke doors, lighted observation windows, access doors and hydraulically operated ash exit doors; each V-section of hopper includes two hopper-type, double-roll grinders with cast iron body and 10-in.-diameter x 2-ft-long manganese steel rolls; 50 hp	310
Total, Area 5	339

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
Area 6--Bottom Ash Conveyance to Disposal Site	
1. Slurry pumps for pipeline conveyance (1 + 1 spare): Centrifugal slurry pumps, 425 gpm, 150-ft head, Ni-Hard liner and impeller, 30-hp motor	44
2. Shutoff and crossover valves (10): Air-operated gate valve, 8-in. I.D. port, Ni-Hard	23
3. One-eighth mile basalt-lined slurry pipeline to dewatering bins, normal use (1): Pipeline comprising 37 18-ft-long sections of flanged, basalt-lined steel pipe, 8-in. I.D. and four basalt-lined elbows or bends, 8-in. I.D.	(46)[a]
4. Spare slurry pipeline to dewatering bins (1): Pipeline comprising 17 40-ft-long sections of flanged steel pipe, 8-in. I.D., schedule 80 carbon steel and 4 hardened elbows or bends, 8-in. I.D.	(12)[a]
5. Dewatering bins for bottom ash slurry (2): Conical-bottom dewatering bins, 25-ft-diameter x 15-ft-high cylindrical section, 19-ft-high cone, 9,000 ft^3, stainless steel floating decanter and movable drainpipe, stationary decanters in conical section, erected for 22-ft railroad clearance, carbon steel bin, stainless steel decanter drum	378
6. Trucks for hauling moist bottom ash to bottom ash landfill (1 + 1 spare): Dump truck with ash haul body, 7-yd^3 capacity, 16,000-lb suspension, 85-hp diesel engine	48
Total, Area 6	493
Area 7--Bottom Ash Disposal Site	
1. Bottom ash landfill (1): Bottom ash landfill, 902-ft square with 1-ft-thick clay liner, volume of 648,000 yd^3, constructed in one 20-ft lift with edge sloped upward at 1-vertical to 2-horizontal (27°), edges and top covered as filled with 1/2-ft-thick layer of clay and 1-1/2-ft-thick layer of topsoil, 20-ft finished	(407)[a]

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
height at edge with top sloped upward to center of landfill at 1-vertical to 29-horizontal (2°), landfill surrounded by runoff and leachate collection ditch 24 ft wide x 2.5 ft deep with 1-ft-thick clay liner; ditch drains to common 260-ft-square catchment basin with 1-ft-thick clay liner; site includes 362-ft-square common topsoil storage area, office trailer with sanitary facilities, equipment storage area, 24-ft-wide access roads, onsite water supply well and 2 peripheral monitoring wells; landfill periphery is enclosed by 6-ft-high security fence	
2. Dozer for moving ash and earth at landfill (1): Same dozer as in Area 3, Item 2 (costed 20% in Area 7 and 80% in Area 3)	15
3. Compactor for ash at landfill (1): Same compactor as Area 3, Item 3 (costed 20% in Area 7 and 80% in Area 3)	18
4. Tank trucks for dust control at landfill (2): Same trucks as in Area 3, Item 4 (costed 20% in Area 7 and 80% in Area 3)	17
5. Front-end loader for stripping and restoring topsoil (1): Same loader as in Area 3, Item 5 (costed 20% in Area 7 and 80% in Area 3)	23
6. Dozer for ash handling (1): Same dozer as in Area 3, Item 6 (costed 20% in Area 7 and 80% in Area 3)	10
7. Service truck for fuel, lubricants, and field service (1): Same service truck as in Area 3, Item 7 (costed 20% in Area 7 and 80% in Area 3)	5
Total, Area 7	88
Area 8--Bottom Ash Water Treatment and Recycle of Water	
1. Settling tank for clarifying water from dewaterin bins (1): Settling tank, 50 ft diameter x 15 ft deep, 220,000 gal, carbon steel	73

(continued)

TABLE 16 (continued)

Item (number): description	Material cost, delivered, 1982 k$
2. Water reservoir for bottom ash dewatering system (1): Water reservoir, 35 ft diameter x 15 ft deep, 108,000 gal, carbon steel	47
3. Recycle pump for underflow solids from settling tank and water reservoir (1): Centrifugal pump, 100 gpm, 100-ft head, carbon steel body and impeller, 5 hp	3
4. Sulfuric acid storage tank for pH control of return water from water reservoir (1): Cylindrical steel tank 5 ft 7 in. diameter x 5 ft 7 in. high, 1,000 gal, flat bottom and closed flat top, carbon steel; all-weather housing	2
5. Metering pump for sulfuric acid to return water (1): Positive displacement metering pump 0.01 to 1 gpm, 0 psig, with flow rate controlled by a pH controller, Carpenter 20 alloy or similar corrosion resistance to 93% sulfuric acid; 0.25 hp	2
6. Sulfuric acid storage tank for pH control of water to discharge (1): Same tank as in Area 4, Item 1 (costed 20% in Area 8 and 80% in Area 4)	0.5
7. Metering pump for sulfuric acid to discharge water (1 + 1 spare): Same pump as in Area 4, Item 2 (costed 20% in Area 8 and 80% in Area 4)	0.5
8. Agitator for mixing of treated water (1): Same agitator as in Area 4, Item 3 (costed 20% in Area 8 and 80% in Area 4)	0.75
9. Pump for solids slurry from water treatment (1 + 1 spare): Same pump as in Area 4, Item 4 (costed 20% in Area 8 and 80% in Area 4)	0.25
10. Automatic sampler for water to discharge (1): Same sampler as in Area 4, Item 5 (costed 20% in Area 8 and 80% in Area 4)	1
Total, Area 8	130
Total, Base Case 5	2,938

a. Costs shown in parentheses are informational and are not included in area or base case totals for equipment material costs.

Ash Collection

The ash collection and storage systems are the same as those described for base case 4 except that some equipment sizes are reduced because of the smaller quantities of ash. The fly ash system is designed for 36 tons/hr instead of the 48 tons/hr of base case 4. Five-inch main conveying lines, smaller separators and storage silos, and a smaller mechanical exhauster are used. Smaller fly ash and bottom ash hoppers and smaller slurry pumps, dewatering bins, and recycle water tanks are used.

Ash Transportation

Fly ash is dumped without moisturizing into 44,000 lb, 20 yd^3 , ash-haul-body dump trucks. The trucks are covered and equipped with tailgate-mounted water tanks. At the landfill the fly ash is unloaded through the moisturizers to provide dust control, additional water is added by tank truck, and the moist ash is immediately spread and compacted. Two fly ash trucks are used on a 56-minute cycle time. Bottom ash is transported in a 7 yd^3 dump truck. The same two shift/day operating schedule used for the other base cases is used.

Landfill

The landfill design and operation is basically the same as the landfill in base case 4. An additional water truck is provided, however. The fly ash landfill occupies 60 acres, has a 2.6 million yd^3 disposal volume, and has a center height of 47 feet. The bottom ash landfill occupies 19 acres, has a 0.6 million yd^3 disposal volume, and a center height of 35 feet. A 90 lb/ft^3 dry bulk density and a 17% moisture content are used for the fly ash landfill while the bottom ash landfill has 10% moisture. The disposal site occupies 116 acres including roads, facilities, and runoff and seepage collection facilities.

RESULTS

The ash disposal costs discussed below are based on similar procedures and formats used in TVA FGD and FGD-waste-disposal economic evaluations. The need of such compatability lies not only in the requirements of evaluation consistency but also in the interrelationships of ash disposal and FGD waste disposal. The overall costs are analyzed from several aspects intended to provide cost breakdowns for comparison of the results with various alternative methods. The total costs are expressed as the sum of various components of direct and indirect costs, and are also itemized separately for fly ash and bottom ash. In addition, the costs are expressed in modular form by functional area (collection, transportation, disposal site, and water treatment and recycle) and by type of equipment or facility (hoppers, process equipment, pipelines, mobile equipment, and disposal site).

DIRECT CAPITAL INVESTMENT

Equipment Costs

Major equipment costs are shown in the equipment lists for each process (Tables 8, 10, 12, 14, and 16). Depending on commercial practice, these costs are for individual items of equipment or package units. Because of design and cost differences between suppliers, the costs are more applicable to comparisons between conceptual design cases than to costs for a particular vendor's system under site-specific conditions.

The equipment costs in Tables 8, 10, 12, 14, and 16 are delivered costs in 1982 dollars and include tax and freight. For slurry pipelines, ponds, and landfills the costs are shown in parentheses but are not included in area totals. In this study the slurry pipelines are considered, along with other piping, as supporting equipment. This procedure allows for the inclusion of slurry pipelines as a transportation function.

The equipment costs for the five base cases are summarized by type of equipment and by area in Table 17. In this table, the costs of hoppers and of mobile equipment are stated separately.

Hoppers are included in this study because the operating costs for ash collection begin with operation of the hoppers. (Therefore operating labor, utilities, and related costs for hopper operation are assigned in the annual revenue requirements.) At the same time, the cost of hoppers exceeds most other equipment costs, ranging from 61% to 23% of the total equipment cost. These cost levels show that hoppers contribute substantially to the equipment costs for ash collection and that their inclusion or exclusion must be

TABLE 17. COSTS OF DELIVERED EQUIPMENT

	1982 k$				
Process equipment	Base case 1	Base case 2	Base case 3	Base case 4	Base case 5
Fly Ash					
Hoppers[a]	421	421	421	421	356
Collection	285	285	285	413	337
Transportation	44	44	39	729	585
Transportation vehicles	0	0	565	211	248
Disposal vehicles	0	0	334	334	350
Water treatment	12	155	24	12	12
Subtotal fly ash	762	905	1,668	2,120	1,888
Bottom Ash					
Hoppers[b]	352	352	352	352	310
Pumps	34	34	18	34	29
Transportation	110	110	108	505	445
Transportation vehicles	0	0	225	53	48
Disposal vehicles	0	0	84	84	88
Water treatment	3	39	6	135	130
Subtotal bottom ash	499	535	793	1,163	1,050
Total Ash					
Hoppers	773	773	773	773	666
Process equipment	488	667	480	1,828	1,538
Vehicles	0	0	1,208	682	734
Total equipment	1,261	1,440	2,461	3,283	2,938

a. Economizer, air heater, and ESP hoppers.
b. Bottom ash hoppers.

recognized. The fly ash hopper costs are based on ESP collection using a single specific collection area (SCA) in all base cases. Changes in the method of collection or SCA could significantly change hopper costs by changing the size of the ESP base to which the hoppers are attached. Since the tonnage of bottom ash is only one-quarter that of fly ash, the cost of bottom ash hoppers is much higher than that of fly ash hoppers relative to the amount of ash collected.

Cases 1 and 2 do not have mobile equipment since the ash is transported by slurry pipelines whose costs are not included as equipment. In base case 3 mobile equipment cost is the largest cost area and in base cases 4 and 5 it constitutes 20% to 25% of the total equipment cost.

Fly ash collection equipment in base case 4 is more expensive than in base cases 1, 2, and 3 because base case 4 has mechanical exhausters and separate collection systems for ESP ash and for economizer and air heater ash. Base case 4 has higher transportation costs, excluding vehicles, because ash storage bins and moisturizers are included as transportation equipment.

With no mobile equipment, base case 1 has the lowest total equipment costs. The addition of pond water treatment and reuse in base case 2 raises equipment costs by a moderate 179 k$ to 1,440 k$. In base case 3, the cost of process equipment is slightly lower than in base case 1 because of lower pump costs for the shorter pipelines but the cost of vehicles, including those required for removing the ash from the ponds, substantially increases the total equipment cost.

Base case 4 has higher costs for fly ash handling equipment. Its fly ash hoppers costs are the same as those in base cases 1, 2, and 3 but the process equipment cost is increased by equipment needed for dry ash collection, storage, and moisturizing for trucking to landfills. Base case 4 also has high processing costs for the mechanized bottom ash dewatering system. Thus, the equipment costs for base case 4 are the highest of the group. For base case 5, the slightly lower equipment cost results mainly from a lower ash tonnage. This reduction is counteracted to some degree by more expensive trucks for conveyance of dry fly ash and by more costly moisturizing at the landfill.

The above comparisons illustrate that the five base cases have widely differing profiles of uninstalled equipment costs. At this level, the costs indicate differences in equipment needs rather than the overall economic standings of the base case processes.

Installed Equipment Costs

The direct capital investments for the five base cases are detailed in Tables 18 through 22. Costs in the equipment lists (Tables 8, 10, 12, 14, and 16) are the basis for the capital investment determinations. They are shown as material costs under the equipment category, along with installation labor costs. Field installation component costs consist of piping and insulation, ductwork, foundations, site preparation, structural, electrical, instrumentation, paint and buildings, as well as costs for services and utilities. Overall costs are itemized by functional area. The column "collection" includes all costs associated with receiving the ash from

TABLE 18. INSTALLED PROCESS EQUIPMENT DIRECT CAPITAL INVESTMENT - BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Fly ash, 1982 k$					Bottom ash, 1982 k$						
Investment Category	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total installed cost	% of total direct investment
Equipment												
Material	706	44	-	12	762	386	110	-	3	499	1,261	8.3
Labor	344	26	-	8	378	215	18	-	1	234	612	4.0
Piping and insulation												
Material	19	389	-	2	410	38	516	-	1	555	965	6.4
Labor	15	156	-	2	173	24	207	-	1	232	405	2.7
Ductwork, chutes, and supports												
Material	2	1	-	0	3	0	0	-	0	0	3	0.0
Labor	4	2	-	0	6	0	0	-	0	0	6	0.0
Concrete foundations												
Material	2	38	-	1	41	8	9	-	1	18	59	0.4
Labor	4	105	-	2	111	24	27	-	1	52	163	1.1
Excavation, site preparations												
Railroad and roads	0	41	-	0	41	0	40	-	0	40	81	0.5
Structural												
Material	5	29	-	0	34	19	0	-	0	19	53	0.3
Labor	8	58	-	0	66	52	0	-	0	52	118	0.8
Electrical												
Material	24	6	-	2	32	13	6	-	1	20	52	0.3
Labor	43	11	-	5	59	20	11	-	2	33	92	0.6
Instruments												
Material	6	3	-	8	17	4	3	-	2	9	26	0.2
Labor	3	1	-	5	9	2	1	-	1	4	13	0.1
Paint and miscellaneous												
Material	1	1	-	1	3	2	1	-	0	3	6	0.0
Labor	7	4	-	6	17	14	2	-	0	16	33	0.2
Buildings												
Material	0	0	-	0	0	0	0	-	0	0	0	0.0
Labor	0	0	-	0	0	0	0	-	0	0	0	0.0
Disposal site												
Ponds	0	0	8,509	0	8,509	0	0	2,127	0	2,127	10,636	70.2
Landfills	-	-	-	-	-	-	-	-	-	-	-	-
Subtotal	1,193	915	8,509	54	10,671	821	951	2,127	14	3,913	14,584	96.1
Services, utilities, and miscellaneous	48	37	340	2	427	33	38	85	1	157	584	3.9
Total direct investment	1,241	952	8,849	56	11,098	854	989	2,212	15	4,070	15,168	100.0
Percent of total direct investment	8.2	6.3	58.3	0.4	73.2	5.6	6.5	14.6	0.1	26.8	100.0	

TABLE 19. INSTALLED PROCESS EQUIPMENT DIRECT CAPITAL INVESTMENT - BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

Investment Category	Fly Ash, 1982 k$					Bottom Ash, 1982 k$					Total installed cost	% of total direct investment
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal		
Equipment												
Material	706	44	-	155	905	386	110	-	39	534	1,440	9.1
Labor	344	26	-	43	413	215	18	-	11	244	657	4.2
Piping and insulation												
Material	19	389	-	145	553	38	516	-	36	590	1,143	7.2
Labor	15	156	-	58	229	24	207	-	15	246	475	3.0
Ductwork, chutes, and supports												
Material	2	1	-	0	3	0	0	-	0	0	3	0.1
Labor	4	2	-	0	6	0	0	-	0	0	6	0.1
Concrete foundations												
Material	2	38	-	16	56	8	9	-	4	21	77	0.5
Labor	4	105	-	42	151	24	27	-	11	62	213	1.3
Excavation, site preparations												
Railroad and roads	0	41	-	0	41	0	40	-	0	40	81	0.5
Structural												
Material	5	29	-	0	34	19	0	-	0	19	53	0.3
Labor	8	58	-	0	66	52	0	-	0	52	118	0.7
Electrical												
Material	24	6	-	12	42	13	6	-	3	22	64	0.4
Labor	43	11	-	20	74	20	11	-	5	36	110	0.7
Instruments												
Material	6	3	-	12	21	4	3	-	3	10	31	0.2
Labor	3	1	-	8	12	2	1	-	2	5	17	0.1
Paint and miscellaneous												
Material	1	1	-	3	5	2	1	-	1	4	9	0.1
Labor	7	4	-	18	29	14	2	-	4	20	49	0.3
Buildings												
Material	0	0	-	12	12	0	0	-	3	3	15	0.1
Labor	0	0	-	16	16	0	0	-	4	4	20	0.1
Disposal site												
Ponds	0	0	8,509	0	8,509	0	0	2,127	0	2,127	10,636	67.2
Landfills	-	-	-	-	-	-	-	-	-	-	-	-
Subtotal	1,193	915	8,509	560	11,177	821	951	2,127	141	4,040	15,217	96.2
Services, utilities, and miscellaneous	48	37	340	22	447	33	38	85	6	162	609	3.8
Total direct investment	1,241	952	8,849	582	11,624	854	989	2,212	147	4,202	15,826	100.0
Percent of total direct investment	7.8	6.0	55.9	3.7	73.4	5.4	6.3	14.0	0.9	26.6	100.0	

TABLE 20. INSTALLED PROCESS EQUIPMENT DIRECT CAPITAL INVESTMENT - BASE CASE 3, HOLDING PONDS AND LANDFILL OF NONHARDENING ASH

Investment Category	Fly Ash, 1982 k$					Bottom Ash, 1982 k$						
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total installed cost	% of total direct investment
Equipment												
Material	706	604	334	24	1,668	370	333	84	6	793	2,461	25.7
Labor	344	26	0	16	386	206	14	0	2	222	608	6.4
Piping and insulation												
Material	19	115	-	4	138	38	166	-	2	206	344	3.6
Labor	15	46	-	4	65	24	67	-	2	93	158	1.7
Ductwork, chutes, and supports												
Material	2	1	-	0	3	0	0	-	0	0	3	0.0
Labor	4	2	-	0	6	0	0	-	0	0	6	0.1
Concrete foundations												
Material	2	12	-	2	16	8	9	-	2	19	35	0.4
Labor	4	34	-	4	42	24	27	-	2	53	95	1.0
Excavation, site preparations												
Railroad and roads	0	12	-	0	12	0	40	-	0	40	52	0.5
Structural												
Material	5	26	-	0	31	19	0	-	0	19	50	0.5
Labor	8	56	-	0	64	52	0	-	0	52	116	1.2
Electrical												
Material	24	6	-	4	34	13	6	-	2	21	55	0.6
Labor	43	11	-	10	64	20	11	-	4	35	99	1.0
Instruments												
Material	6	3	-	16	25	4	3	-	4	11	36	0.4
Labor	5	1	-	10	16	2	1	-	3	6	22	0.2
Paint and miscellaneous												
Material	1	1	-	2	4	2	1	-	1	4	8	0.1
Labor	7	4	-	12	23	14	2	-	1	17	40	0.4
Buildings												
Material	0	0	-	0	0	0	0	-	0	0	0	0.0
Labor	0	0	-	0	0	0	0	-	0	0	0	0.0
Disposal site												
Ponds	0	0	2,534	0	2,534	0	0	608	0	608	3,142	32.9
Landfills	0	0	1,491	0	1,491	0	0	372	0	372	1,863	19.5
Subtotal	1,195	960	4,359	108	6,622	796	680	1,064	31	2,571	9,193	96.2
Services, utilities, and miscellaneous	48	38	174	5	265	32	27	43	1	103	368	3.8
Total direct investment	1,243	998	4,533	113	6,887	828	707	1,107	32	2,674	9,561	100.0
Percent of total direct investment	13.0	10.4	47.4	1.2	72.0	8.7	7.4	11.6	0.3	28.0	100.0	

TABLE 21. INSTALLED PROCESS EQUIPMENT DIRECT CAPITAL INVESTMENT - BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

Investment Category	Fly Ash, 1982 k$					Bottom Ash, 1982 k$						
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total installed cost	% of total direct investment
Equipment												
Material	834	940	334	12	2,120	386	558	84	135	1,163	3,283	39.0
Labor	406	328	0	8	742	215	252	0	41	508	1,250	14.9
Piping and insulation												
Material	19	19	-	2	40	38	66	-	34	138	178	2.1
Labor	15	15	-	2	32	24	29	-	15	68	100	1.2
Ductwork, chutes, and supports												
Material	2	1	-	0	3	0	0	-	0	0	3	0.0
Labor	4	2	-	0	6	0	0	-	0	0	6	0.1
Concrete foundations												
Material	3	32	-	1	36	8	23	-	25	56	92	1.1
Labor	7	85	-	2	94	24	61	-	64	149	243	2.9
Excavation, site preparations												
Railroad and roads	0	6	-	0	6	0	1	-	0	1	7	0.1
Structural												
Material	5	20	-	0	25	19	12	-	8	39	64	0.8
Labor	8	35	-	0	43	52	28	-	14	94	137	1.6
Electrical												
Material	24	6	-	2	32	13	2	-	4	19	51	0.6
Labor	48	11	-	5	64	20	7	-	9	36	100	1.2
Instruments												
Material	6	0	-	8	14	4	0	-	5	9	23	0.3
Labor	3	0	-	5	8	2	0	-	3	5	13	0.2
Paint and miscellaneous												
Material	2	2	-	1	5	2	1	-	4	7	12	0.1
Labor	14	14	-	6	34	14	8	-	26	48	82	1.0
Buildings												
Material	0	0	-	0	0	0	0	-	0	0	0	0.0
Labor	0	0	-	0	0	0	0	-	0	0	0	0.0
Disposal site												
Ponds	-	-	-	-	-	-	-	-	-	-	-	-
Landfills	0	0	1,946	0	1,946	0	0	487	0	487	2,433	29.0
Subtotal	1,400	1,516	2,280	54	5,250	821	1,048	571	387	2,827	8,077	96.2
Services, utilities, and miscellaneous	56	61	91	2	210	33	42	23	15	113	323	3.8
Total direct investment	1,456	1,577	2,371	56	5,460	854	1,090	594	402	2,940	8,400	100.0
Percent of total direct investment	17.3	18.6	28.2	0.7	65.0	10.2	12.9	7.1	4.8	35.0	100.0	

TABLE 22. INSTALLED PROCESS EQUIPMENT DIRECT CAPITAL INVESTMENT - BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

Investment Category	Fly Ash, 1982 k$					Bottom Ash, 1982 k$						
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total installed cost	% of total direct investment
Equipment												
Material	693	833	350	12	1,888	339	493	88	130	1,050	2,938	40.5
Labor	337	263	0	8	608	178	209	0	39	426	1,034	14.3
Piping and insulation												
Material	16	15	-	2	33	32	66	-	34	132	165	2.3
Labor	12	12	-	2	26	20	29	-	15	64	90	1.2
Ductwork, chutes, and supports												
Material	2	1	-	0	3	0	0	-	0	0	3	0.0
Labor	3	2	-	0	5	0	0	-	0	0	5	0.1
Concrete foundations												
Material	3	26	-	1	30	7	19	-	21	47	77	1.1
Labor	7	68	-	2	77	20	50	-	52	122	199	2.7
Excavation, site preparations												
Railroad and roads	0	5	-	0	5	0	1	-	0	1	6	0.1
Structural												
Material	2	16	-	0	18	16	11	-	7	34	52	0.7
Labor	3	28	-	0	31	43	25	-	11	79	110	1.5
Electrical												
Material	21	4	-	2	27	11	2	-	4	17	44	0.6
Labor	39	9	-	5	53	17	7	-	9	33	86	1.2
Instruments												
Material	6	0	-	8	14	4	0	-	5	9	23	0.3
Labor	3	0	-	5	8	2	0	-	3	5	13	0.2
Paint and miscellaneous												
Material	2	2	-	1	5	2	1	-	4	7	12	0.2
Labor	14	11	-	5	30	11	8	-	22	41	71	1.0
Buildings												
Material	0	0	-	0	0	0	0	-	0	0	0	0.0
Labor	0	0	-	0	0	0	0	-	0	0	0	0.0
Disposal site												
Ponds	-	-	-	-	-	-	-	-	-	-	-	-
Landfills	0	0	1,630	0	1,630	0	0	407	0	407	2,037	28.1
Subtotal	1,163	1,295	1,980	53	4,491	702	921	495	356	2,474	6,965	96.1
Services, utilities, and miscellaneous	46	52	79	2	180	28	37	20	14	99	279	3.9
Total direct investment	1,209	1,347	2,059	55	4,671	730	958	515	370	2,573	7,244	100.0
Percent of total direct investment	16.7	18.6	28.4	0.8	64.5	10.1	13.2	7.1	5.1	35.5	100.0	

the boiler, or ESP's; for bottom ash it is primarily hopper costs and for fly ash it is primarily hoppers and pneumatic conveying equipment costs. The column "transportation to disposal site" includes pipelines, trucks, and other process equipment required for transportation. Depending on the particular process, it includes dewatering bins, silos, pumps, and front loaders. The column "disposal site" contains only ponds, landfills, and mobile equipment. The column "water treatment and recycle" includes the facilities required for the sampling and pH control of effluent water and for scale control of recirculated transport water.

The pond and landfill construction costs are detailed in Table 23. The costs shown represent only the disposal site construction costs and do not include land or mobile equipment. The four largest cost areas involve the movement and placement of earth. Because of this, pond construction costs are almost five times those of landfills for comparable situations (base cases 1 and 2 compared with base case 4). Ponds require a larger area than landfills for equivalent quantities of waste because of the lower bulk density of the waste and the shallower waste depth. Landfills can be sloped upward from the edge to the center whereas increasing pond depth requires an exponentially increasing quantity of dike material. Ponds also require excavation of a substantial quantity of subsoil for dike construction. As a result, the construction cost for landfills even when fully capitalized is substantially lower than that for ponds. Against this, however, must be weighed the higher equipment costs and operating costs for landfills.

TOTAL CAPITAL INVESTMENT

Total capital investments for the five base cases are summarized in Table 24. They consist of the direct capital investment plus indirect investment, contingency, other capital investment, land, and working capital. Detailed capital investment tables are included in Appendix A. Base case 1, direct ponding of nonhardening ash without water reuse, represents an industry standard, and can serve as a basis of comparison for other disposal practices represented by base cases 2 through 4.

Base case 2, direct ponding of nonhardening ash with water reuse, is the same as base case 1 except that the sluice water is treated and returned to the power plant for reuse as sluicing water. Both direct capital investment and total capital investment are increased about 4% by this addition.

The base case 3 capital investment is only two-thirds of that of base case 1. The base case 3 capital investment for 5-year ponds and a 25-year landfill are only one-half those of base case 1 for a 30-year pond. This difference more than offsets the mobile equipment costs of base case 3.

Base case 4, direct landfill of nonhardening ash, differs from base case 3 largely in capital investment for transportation and for the disposal site. Direct investment for transportation in base case 4 is one-third less than those of base case 3 because of the elimination of sluicing to the temporary ponds and of ash removal from the ponds. This reduction in costs occurs in spite of the addition of the bottom ash dewatering system and the fly ash silos. Similarly, elimination of the temporary ponds reduces disposal site direct investment by about one-half for base case 4, compared with base case 3, or by three-quarters when compared with base case 1.

TABLE 23. POND AND LANDFILL CONSTRUCTION COSTS

1982 k$

	Base cases 1 and 2			Base case 3			
	Fly ash pond	Bottom ash pond	Total	Fly ash pond	Bottom ash pond	Common landfill	Total
Land clearance	253	90	343	69	25	99	193
Excavation, soil storage	2,926	1,049	3,975	810	296	317	1,423
Dike construction	1,676	633	2,309	594	191	-	785
Liner installation	927	295	1,222	216	65	439	720
Catchment ditch, basin	-	-	-	0	0	211	211
Discharge ditch	-	-	50	-	-	19	45
Road construction on dikes	52	29	81	25	14	0	39
Site facilities: fences, trailer/office, monitoring wells, access roads	-	-	344	-	-	197	393
Reclamation	-	-	2,312	-	-	581	1,196
Total construction cost	8,509	2,127	10,636	2,534	608	1,863	5,005
Volume, Myd^3	5.54	1.39	6.93	.94	.23	3.51	

(continued)

TABLE 23 (continued)

	Base case 4			Base case 5		
	Fly ash landfill	Bottom ash landfill	Total	Fly ash landfill	Bottom ash landfill	Total
Land clearance	95	33	128	79	26	105
Excavation, soil storage	331	108	439	282	92	374
Dike construction	-	-	-	-	-	-
Liner installation	424	132	556	339	105	444
Catchment ditch, basin	-	-	295	-	-	255
Discharge ditch	-	-	19	-	-	17
Road construction on dikes	-	-	-	-	-	-
Site facilities: fences, trailer/office, monitoring wells, access roads	-	-	222	-	-	204
Reclamation	-	-	774	-	-	638
Total construction cost	1,946	487	2,433	1,630	407	2,037
Volume, Myd^3	3.37	.84	4.21	2.57	0.65	3.22

TABLE 24. BASE CASE SUMMARIES OF CAPITAL INVESTMENTS

	Direct capital investment, 1982 k$		Total capital investment,[a] 1982 k$	
	k$	$/kW	k$	$/kW
Base Case 1				
Fly ash	11,098	22.2	18,881	37.8
Bottom ash	4,070	8.1	6,979	14.0
Total	15,168	30.3	25,860	51.7
Base Case 2				
Fly ash	11,624	23.2	19,801	39.6
Bottom ash	4,202	8.4	7,221	14.4
Total	15,826	31.7	27,022	54.0
Base Case 3				
Fly ash	6,887	13.8	11,628	23.3
Bottom ash	2,674	5.3	4,501	9.0
Total	9,561	19.1	16,129	32.3
Base Case 4				
Fly ash	5,460	10.9	9,652	19.3
Bottom ash	2,940	5.9	5,101	10.2
Total	8,400	16.8	14,753	29.5
Base Case 5				
Fly ash	4,671	9.3	8,190	16.4
Bottom ash	2,573	5.1	4,455	8.9
Total	7,244	14.5	12,645	25.3

[a] Total capital investment consists of direct capital investment plus indirect investment, contingency, other capital investment, land, and working capital.

The capital investment of base case 5, direct landfill of self-hardening ash, cannot be compared directly with the similar base case 4 disposal technique for nonhardening ash because the quantities of ash differ. For the self-hardening ash the total ash rate is about 48,000 lb/hr whereas it is about 62,000 lb/hr for the nonhardening ash. Consequently, costs related to ash quantities are generally lower in all areas. Except for ash quantities, however, the processes are similar in all areas except for the manner in which the fly ash is transported. For the nonhardening fly ash, moisturizers attached to the storage silos wet the ash as it is loaded into open-bed trucks. The same trucks are used to transport bottom ash. For the self-hardening fly ash moisturizers are attached to covered-bed trucks. Bottom ash is hauled in separate trucks. In terms of capital investment the differences in these two methods is minimal. The trucks for the self-hardening fly ash are more expensive because of the covers and self-contained moisturizers but this cost difference is counteracted by the elimination of bin moisturizers. Consequently, the higher capital investment for direct landfill disposal of nonhardening ash compared with direct landfill disposal of self-hardening ash is essentially a result of the larger quantity of ash.

The major cost elements in capital investment for the five base cases are shown in Table 25 as percentages of the total capital investment. The comparisons show the differences in the distribution of capital investment between ponding and landfill disposal cases. Disposal site capital investment dominates the area costs in the pond cases whereas investments for landfill disposal are more equally distributed among collection, transportation, and the disposal site. Water treatment and transportation for reuse is a minor element for both types of disposal. Land costs are proportionately lower for landfill disposal than pond disposal.

TABLE 25. MAJOR COST ELEMENTS IN CAPITAL INVESTMENT

	Percentage of total capital investment				
Base case:	1	2	3	4	5
Cost Element					
Ash collection	8	8	13	16	16
Ash transportation	7	7	10	18	18
Disposal site	43	43	35	20	20
Water treatment and recycle	-	3	1	3	3
Proportioned costs[a]	34	31	34	38	38
Land	8	8	7	5	5

a. Indirect investment, contingency, other capital investment, working capital.

ANNUAL REVENUE REQUIREMENTS

The annual revenue requirements for the five base cases are summarized in Table 26. Detailed annual revenue requirement tables for each base case are shown in Appendix A. The results shown in Table 26 are first-year annual revenue requirements using levelized capital charges, as described in the premises. Levelized annual revenue requirements, representing annual revenue requirements inflated and discounted over the 30-year life of the power plant, are also shown in Appendix A.

Base case 1, direct ponding of nonhardening ash without water reuse, representing established practice, serves as a basis of comparison with other disposal practices represented by base cases 2 through 4. Base case 2, direct ponding of nonhardening ash with water reuse, differs from base case 1 only in the treatment and return of the sluice water to the power plant. This increases the annual revenue requirements by 7%, from 1.85 to 1.98 mills/kWh. The largest increase in direct cost is for maintenance, followed by electricity, water treatment reagents, operating labor, and sampling and analyses. There is only a small direct cost saving in water costs.

Base case 3, temporary ponding of nonhardening ash and final disposal by landfill, has annual revenue requirements of 1.91 mills/kWh, which are not appreciably different from the direct ponding annual revenue requirements of base cases 1 and 2. The direct costs of base case 3, however, are twice those of base cases 1 and 2. The higher direct costs for base case 3 are primarily a result of much higher labor costs (0.32 mills/kWh versus 0.08 mills/kWh for base case 1) and large costs for diesel fuel (0.07 mills/kWh) and dredging fly ash from the temporary pond (0.07 mills/kWh), which do not appear in direct ponding disposal. In contrast, the indirect costs of base case 3 are substantially lower, primarily because of the lower capital charges.

Base case 4, direct landfill of nonhardening ash, has lower annual revenue requirements, 1.66 mills/kWh, than either direct ponding (base cases 1 and 2) or temporary ponding followed by landfill (base case 3). Direct costs for base case 4 are similar in structure to base case 3 although generally lower because the pipeline transportation electricity and maintenance costs and the pond dredging and loading costs are eliminated. The most important differences are a reduction of 0.07 mill/kWh in dredging, 0.04 mill/kWh in labor, and 0.03 mill/kWh in diesel fuel. In contrast, overall maintenance costs are 0.02 mill/kWh higher for base case 4. Indirect costs for base case 4 are also similar in pattern to base case 3 but somewhat lower because of the lower overheads and capital charges.

Base case 5, direct landfill of self-hardening ash has the lowest annual revenue requirements of the five base cases, 1.57 mills/kWh. Most of the differences between the annual revenue requirements of base case 5 and base case 4, direct landfill of nonhardening ash, are results of the smaller quantity of ash in base case 5. Differences in direct costs related directly to process differences are due to higher labor and water treatment costs for base case 5. Labor costs are 8% higher because of separate trucks for fly and bottom ash transportation and the more complicated moisturizing of fly ash at the landfill. Water treatment costs are four times higher in base case 5 because of the high alkalinity of the ash.

TABLE 26. BASE CASE SUMMARIES OF ANNUAL REVENUE REQUIREMENTS

	Direct costs, 1984 $			Total annual revenue,[a] 1984 $		
	k$	Mills/kWh	$/ton, dry	k$	Mills/kWh	$/ton, dry
Base Case 1						
Fly ash	515	0.19	3.75	3,571	1.30	26.01
Bottom ash	313	0.11	9.12	1,514	0.55	44.12
Total	828	0.30	4.82	5,085	1.85	29.63
Base Case 2						
Fly ash	605	0.22	4.41	3,842	1.40	27.99
Bottom ash	343	0.12	9.98	1,595	0.58	46.47
Total	948	0.34	5.52	5,437	1.98	31.68
Base Case 3						
Fly ash	1,411	0.51	10.28	3,848	1.40	28.03
Bottom ash	481	0.18	14.01	1,402	0.51	40.84
Total	1,892	0.69	11.03	5,250	1.91	30.59
Base Case 4						
Fly ash	1,004	0.36	7.31	2,954	1.08	21.52
Bottom ash	544	0.20	15.84	1,600	0.58	46.63
Total	1,548	0.56	9.02	4,554	1.66	26.54
Base Case 5						
Fly ash	996	0.36	9.49	2,736	1.00	26.06
Bottom ash	585	0.21	22.28	1,575	0.57	59.99
Total	1,581	0.57	12.05	4,311	1.57	32.84

a. Total annual revenue requirements consist of direct costs and indirect costs; indirect costs are made up of overheads and capital charges.

In comparison of costs per ton of ash, the costs for base cases 1 through 4, ranging from about 32 $/dry ton for base case 2 to about 27 $/dry ton for base case 4, have the same proportional differences as the annual revenue requirements because the same quantities of ash are involved. Although base case 5 has the lowest annual revenue requirements, the cost per ton of ash is almost 33 $/dry ton because of the smaller quantity involved, the usual effect of economy of scale.

The major costs in annual revenue requirements are shown in Table 27 as percentages of the total annual revenue requirements. As in capital investment, basic differences exist between ponding and landfill disposal. In the landfill cases the proportion of the costs for operating labor is four to five times that of the ponding cases. This is due to the operating labor for mobile equipment. Similarly, overheads that depend on operating labor are twice as high, proportionately, for landfill as for ponding. On the other hand, the proportion for total capital charges for landfill is only 60% of that for ponding. The cost distribution of base case 3, temporary ponding followed by landfill, is similar to the direct landfill cases. Maintenance constitutes about 10% of the costs regardless of the disposal method. Utilities, including diesel fuel, are also a small cost regardless of the disposal method.

TABLE 27. MAJOR COST ELEMENTS IN

ANNUAL REVENUE REQUIREMENTS

	Percentage of total annual revenue requirements[a]				
Base case:	1	2	3	4	5
Cost Element					
Labor	4	4	17	17	20
Process reagents	-	-	-	-	2
Utilities					
Electricity	1	2	1	1	-
Diesel fuel	-	-	4	3	3
Maintenance	10	10	9	12	11
Sampling and analysis	1	1	1	1	1
Dredging	-	-	4	-	-
Overheads	9	9	19	18	20
Capital charges	75	73	45	47	43

a. Rounded to nearest whole number, costs less than 0.5% omitted.

MODULAR CAPITAL INVESTMENT AND ANNUAL REVENUE REQUIREMENTS

Ash disposal methods can be conveniently categorized by the types of equipment and facilities used or by the types of functions employed. Most methods employ combinations of diverse types of equipment and facilities that can be readily identified as units in the operation. In the same manner most methods employ combinations of discrete functions that can be similarly identified. Such divisions are useful in economic analyses, both in determining the relative importance of different equipment, facilities, and functions in overall costs and in projecting conclusions drawn from specific analyses to more general situations. Modular costs were developed in this study for both equipment and facility and functional modules.

Modular Costs by Type of Equipment and Facility Area

The modular cost divisions by equipment type and facility area consist of five areas: hoppers, process equipment, pipelines, mobile equipment, and ponds and landfill. The hopper area includes only the bottom ash, economizer, air heater, and ESP ash hoppers. These are shown separately from other process equipment because they constitute so large a portion of process equipment costs. The process equipment area comprises all other process equipment such as the water supply system (including pond return lines), all pumps (including ash pumps), air conveying systems, dewatering systems, and storage silos. The pipeline area consists only of the slurry pipelines. Mobile equipment comprises all trucks and earthmoving equipment. The disposal site area comprises all costs associated with the disposal sites except mobile equipment. Summaries of the modular capital investment and annual revenue requirements for the five base cases are shown in Tables 28 and 29 and Figure 22. Detailed data are shown in Tables B-1 through B-10 in Appendix B.

Capital investment by type of equipment illustrates that different types of equipment have very different total capital investments compared with uninstalled equipment cost. Different types of equipment have very different installation and indirect costs. For example, in proceeding from equipment cost to total capital investment, hoppers increase three times in cost. Mobile equipment costs increase only 14%.

Modular Capital Investment by Type of Equipment and Facility Area--

In the hopper category, capital investment remains essentially constant regardless of the disposal method, changing only in base case 5 because of the smaller ash quantity. Although hopper costs are not, in general, affected by subsequent ash handling, a variety of factors could greatly affect their costs. In this study ESP's with a single SCA were assumed for fly ash collection. Different collection methods, ESP designs, SCA's, and different design philosophies could affect hopper costs.

Process equipment varies from a minor to a major portion of capital investment depending on the disposal method. In base case 1 process equipment, consisting mainly of the fly ash pneumatic system and the water supply systems, is a relatively minor cost element. In base case 2 these costs are increased about one-third by inclusion of the water treatment system. Base case 3 has the lowest process equipment capital investment, although it constitutes a larger portion of the total capital investment. In this case the ash transportation pumping requirements are reduced because the

TABLE 28. MODULAR CAPITAL INVESTMENT BY EQUIPMENT AND FACILITY AREAS

	Equipment or facility area, 1982 $						
	Hoppers	Process	Pipeline	Mobile equipment	Pond	Landfill	Total
Base Case 1							
k$	2,591	2,457	2,500	0	18,312	0	25,860
%	10	9	10	0	71	0	
Base Case 2							
k$	2,591	3,619	2,500	0	18,312	0	27,022
%	10	13	9	0	68	0	
Base Case 3							
k$	2,591	2,349	698	1,382	5,382	3,727	16,129
%	16	15	4	9	33	23	
Base Case 4							
k$	2,591	6,385	141	780	0	4,856	14,753
%	18	43	1	5	0	33	
Base Case 5							
k$	2,231	5,376	143	839	0	4,054	12,645
%	18	42	1	7	0	32	

TABLE 29. MODULAR ANNUAL REVENUE REQUIREMENTS BY EQUIPMENT AND FACILITY ARFAS

	Equipment or facility area, 1984 $						
	Hoppers	Process	Pipeline	Mobile equipment	Pond	Landfill	Total
Base Case 1							
k$	704	827	483	0	3,071	0	5,085
%	13.8	16.3	9.5	0	60.4	0	
Base Case 2							
k$	704	1,142	483	0	3,108	0	5,437
%	12.9	21.0	8.9	0	57.2	0	
Base Case 3							
k$	704	842	136	1,599	1,201	768	5,250
%	13.4	16.0	2.6	30.5	22.9	14.6	
Base Case 4							
k$	704	1,657	31	1,198	0	965	4,555
%	15.4	36.4	0.7	26.3	0	21.2	
Base Case 5							
k$	625	1,519	31	1,309	0	827	4,311
%	14.5	35.2	0.7	30.4	0	19.2	

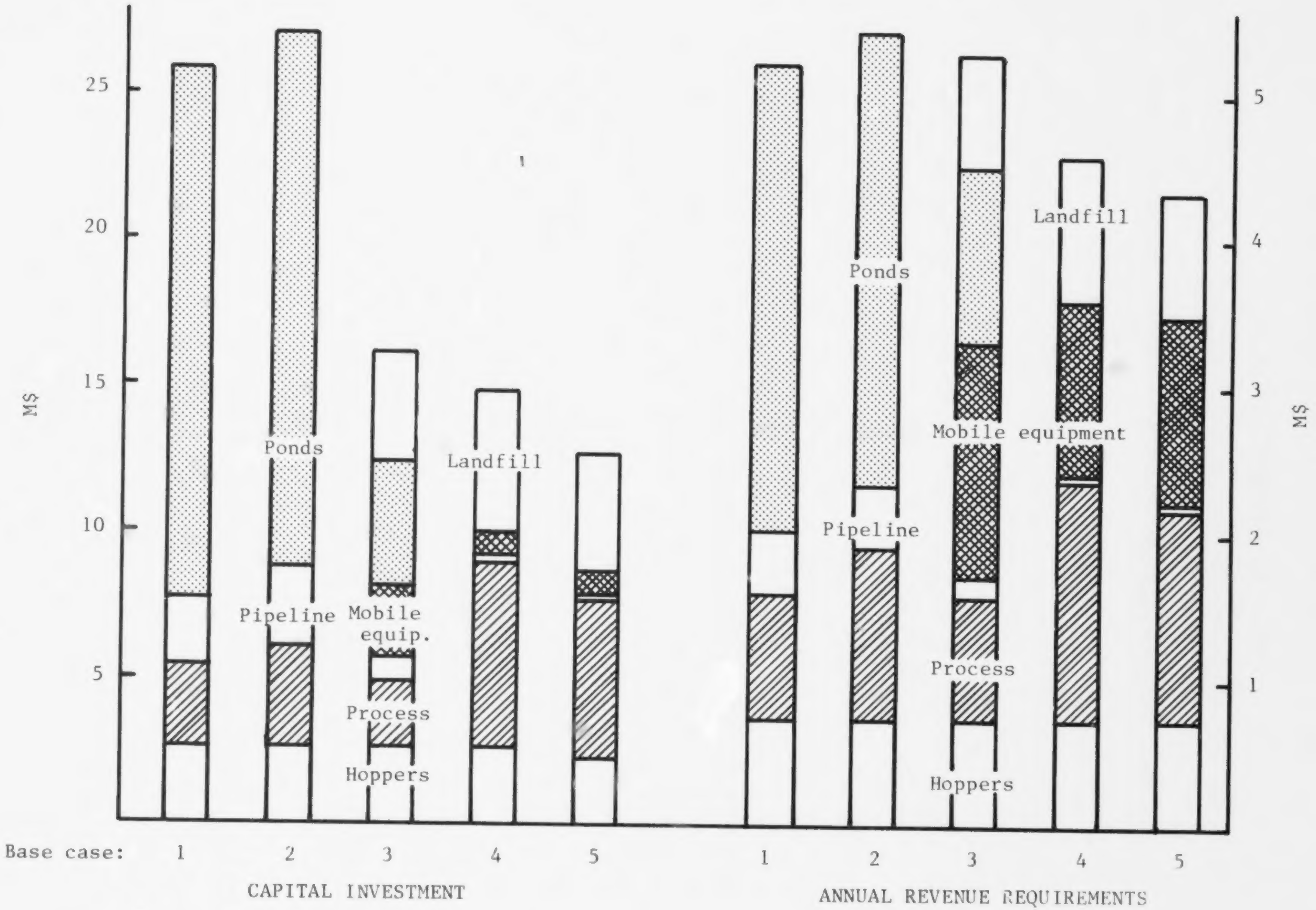

Figure 22. Modular costs by equipment and facility area.

ponds are only one-fourth mile away. In base cases 4 and 5, direct landfill disposal, process equipment is increased by inclusion of the bottom ash dewatering system and fly ash silos. These roughly double process equipment capital investment compared with the pond disposal cases.

Pipeline capital investment is essentially equivalent to hopper and process equipment capital investment in base cases 1 and 2. In base case 3, pipeline investment is reduced almost in proportion to the length reduction from one mile to one-fourth mile. The short bottom ash transport line to the dewatering bins in base cases 4 and 5 is not a significant factor in capital investment.

Mobile equipment is a minor element of capital investment, constituting only 5% and 7% of base cases 4 and 5 total capital investment. In terms of capital investment dry trucking and placement is two-thirds less expensive than wet sluicing over the one-mile distance.

In base cases 1 and 2 pond costs constitute two-thirds of the capital investment. The effect of pond size is seen in base case 3, which has 5-year rather than 30-year ponds. A sixfold reduction in pond capacity is accompanied by only a three-fold reduction in pond costs. In comparison, landfill capital investment is about one-fourth that for ponds.

Modular Annual Revenue Requirements by Type of Equipment and Facility Area--

The cost distribution of annual revenue requirements is strongly influenced by capital charges derived from the capital investment. The effect of capital charges is variable depending on the type of equipment or facility, as the comparison of base case 1 and base case 4 taken from Tables B-2 and B-8 illustrate for comparable pond and landfill disposal methods.

	Annual revenue requirements - 1984 k$						
	Hoppers	Process	Pipeline	Mobile equipment	Ponds	Landfills	Total
Base Case 1							
Direct	202	317	72	-	237	-	828
Capital charges	381	361	368	-	2,692	-	3,801
Overheads	121	149	43	-	142	-	456
Total	704	827	483		3,071		5,085
Capital charges, %	54	44	76		88		75
Base Case 4							
Direct	202	460	6	723	-	157	1,548
Capital charges	381	937	22	115	-	714	2,169
Overheads	121	260	3	360	-	94	839
Total	704	1,657	31	1,198		965	4,555
Capital charges, %	54	57	71	10		74	48

The annual revenue requirements for ponds, landfills and pipelines are particularly affected. Capital charges account for almost nine-tenths of pond annual revenue requirements and almost three-fourths of landfill and pipeline annual revenue requirements. At the opposite extreme, capital charges constitute only one-tenth of the mobile equipment annual revenue requirements. As a result, there is a large difference between direct and indirect cost ratios for the pond and the landfill disposal methods. For pond disposal, capital charges account for three-fourths of the annual revenue requirements; for landfill disposal, capital charges account for only one-half.

In terms of direct costs, therefore, pond disposal is a low-cost disposal method, costing only one-half as much as landfill disposal. This is achieved, however, by a large capital expenditure for ponds, which increases the total annual revenue requirements above those for landfill disposal.

In terms of equipment areas, annual revenue requirements for hoppers are the same regardless of the disposal method employed, constituting about one-seventh of the total for all five base cases. Process equipment annual revenue requirements constitute about one-sixth of the total for pond disposal. Water reuse, requiring treatment and return, increases process equipment annual revenue requirements by one-third. Process equipment annual revenue requirements for landfill disposal are more than one-third of the total annual revenue requirements because of the additional dewatering, storage, and loading operations required. Base case 3, temporary ponding and landfill, has process equipment annual revenue requirements similar to those for pond disposal because dewatering, storage, and loading costs are functions of the mobile equipment and pond areas.

Pipeline area annual revenue requirements for base cases 1 and 2 are relatively minor cost factors. In contrast, mobile equipment annual revenue requirements are over twice as high and constitute about one-fourth of the total annual revenue requirements for landfill disposal.

Pond annual revenue requirements are by far the largest cost element in base cases 1 and 2. The predominance of capital charges in these costs has been discussed. Direct costs for ponds consist largely of maintenance costs. Water treatment costs are minimal, as shown by the small difference between base case 1 and base case 2 pond area annual revenue requirements. The influence of capital charges acts to decrease pond disposal area (pond plus landfill) annual revenue requirements for base case 3. This occurs even though there are substantial additional costs for landfill.

Landfill area annual revenue requirements are also dominated by capital charges. These are, however, much lower than pond capital charges because of the lower landfill construction costs. Landfill direct costs consist largely of operating labor and maintenance.

Modular Costs by Process Area

The modular divisions by process area consist of four areas: collection, transportation, disposal site, and water treatment and reuse. These four areas are, in turn, subdivided into bottom ash and fly ash areas. In cases where the allocation of costs cannot be made on the basis of specific equipment functions, or flow rates, (water treatment for example) it is made on the basis of ash quantities. Eighty percent of the costs are assigned to fly ash and 20% to bottom ash in these cases. The equipment lists show the modular equipment divisions upon which the cost divisions are based. They also show the proration of costs for equipment common to both fly ash and bottom ash.

The collection area consists of the ash hoppers, a portion of the water supply systems, and the fly ash pneumatic systems including the vacuum producers. The transportation area consists of air separators, a portion of the water supply systems, ash pumps, the pipeline systems, trucks, storage silos and moisturizers, the bottom ash dewatering bins, and removal of ash from temporary ponds. The disposal area consists of ponds and landfills, including all mobile equipment except that used to load and haul ash. The water treatment and recycle area consists of the treatment systems, pumps and return lines, and the bottom ash water systems. Modular costs by process area for base cases 1 through 5 are summarized in Tables 30 and 31. Detailed data are shown in Tables B-11 through B-20 in Appendix B.

Modular Capital Investment by Process Area--

Collection area capital investments do not differ greatly. Most of the direct costs are associated with hoppers and the fly ash collection systems that are similar for all processes. The collection area capital investment for base case 4 is higher because of the separation equipment and mechanical exhaustor used for dry fly ash collection. These costs are also included in the base case 5 collection area but the total collection area capital investment is reduced because of the smaller quantity of ash.

Depending on the method of disposal, transportation capital investment consists largely of pipeline, mobile equipment, and storage and dewatering equipment costs. In base cases 1 and 2 the mile-long pipelines are the major cost. The base case 3 capital investment is lower because of the reduced costs for the quarter-mile-long pipelines. This reduction is greater than the additional capital investment for trucks and loaders. In base cases 4 and 5, the bottom ash dewatering bins and fly ash silos constitute the major expense.

Pond and landfill construction costs are the only substantial disposal area capital investments. Mobile equipment capital investment is only about one-tenth of disposal site capital investment for landfill disposal. Because of the large capital investment for pond construction, base cases 1 and 2 have disposal site capital investments more than three times larger than base case 4 and about two times those of base case 3. In all five base cases disposal site capital investment is the highest cost area, ranging from about 70% of the total for direct ponding to 36% of the total for direct landfill disposal.

The capital investment for water treatment and recycle is a relatively small component of the total capital investment. For base case 1, in which the sluice water is simply treated for pH control before discharge, the capital investment is less than 0.3 $/kW. This is increased to 2.6 $/kW, 5% of the total capital investment, by additional treatment to control scaling and recycle. About two-thirds of this increase is the one-mile-long return water pipeline. In base case 3, with both pond and landfill effluent water

TABLE 30. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

	1982 k$				
	Collection	Transportation	Disposal site	Water treatment and recycle	Total
Base Case 1					
Fly ash	2,337	1,791	14,648	105	18,891
Bottom ash	1,524	1,765	3,662	28	6,979
Total	3,861	3,556	18,310	133	25,860
%	15	13	71	1	100
Base Case 2					
Fly ash	2,337	1,791	14,648	1,025	19,801
Bottom ash	1,524	1,765	3,662	270	7,221
Total	3,861	3,556	18,310	1,295	27,022
%	14	13	68	5	100
Base Case 3					
Fly ash	2,340	1,452	7,620	216	11,628
Bottom ash	1,481	1,095	1,868	57	4,501
Total	3,821	2,547	9,488	273	16,129
%	23	16	59	2	100
Base Case 4					
Fly ash	2,734	2,582	4,231	105	9,652
Bottom ash	1,524	1,824	1,064	689	5,101
Total	4,258	4,406	5,295	794	14,753
%	29	30	36	5	100
Base Case 5					
Fly ash	2,272	2,204	3,609	105	8,190
Bottom ash	1,304	1,610	903	638	4,455
Total	3,576	3,814	4,512	743	12,645
%	28	30	36	6	100

TABLE 31. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

	1984 k$				
	Collection	Transportation	Disposal site	Water treatment and recycle	Total
Base Case 1					
Fly ash	681	385	2,451	54	3,571
Bottom ash	423	442	615	34	1,514
Total	1,105	827	3,065	88	5,085
%	22	16	60	2	100
Base Case 2					
Fly ash	681	380	2,451	330	3,842
Bottom ash	423	440	615	116	1,595
Total	1,105	821	3,065	446	5,437
%	20	15	57	8	100
Base Case 3					
Fly ash	680	1,219	1,837	112	3,848
Bottom ash	409	474	456	62	1,402
Total	1,089	1,692	2,294	174	5,250
%	21	32	44	3	100
Base Case 4					
Fly ash	751	798	1,348	57	2,954
Bottom ash	420	535	350	296	1,600
Total	1,171	1,333	1,698	354	4,555
%	26	29	37	8	100
Base Case 5					
Fly ash	647	747	1,285	57	2,736
Bottom ash	365	494	324	387	1,575
Total	1,012	1,241	1,609	444	4,311
%	24	29	37	10	100

treatments, capital investment is only 0.5 $/kW. In base cases 4 and 5 most of the capital investment for water treatment and recycle is for bottom ash sluice water treatment and recycle.

Modular Annual Revenue Requirements by Process Area--

Capital charges have an effect on the modular annual revenue requirements by process area similar to, though less extensive than, their effect on modular annual revenue requirements by type of equipment. As shown below for base cases 1 and 4 taken from Tables B-12 and B-18, the capital charge component of the modular annual revenue requirements varies from 88% to 23%.

	Collection	Trans- portation	Disposal site	Water treatment and recycle	Total
Base Case 1					
Direct	350	201	234	43	829
Capital charges	568	523	2,692	20	3,801
Overheads	187	104	140	26	456
Total	1,105	827	3,065	88	5,085
Capital charges, %	51	63	88	23	75
Base Case 4					
Direct	348	444	607	149	1,548
Capital charges	626	648	778	117	2,169
Overheads	197	241	312	89	839
Total	1,171	1,333	1,698	354	4,555
Capital charges, %	53	49	46	33	48

Costs for the pond disposal site are largely composed of capital charges because few operating costs are associated with pond disposal. In contrast, capital charges for the landfill disposal site are only 46% of the total annual revenue requirements. This results both from the larger operating costs and from the lower capital investment. The capital charge component of annual revenue requirements for the other process areas are less extreme and differ less between the two disposal processes than they do for the modular categorization by type of equipment. The categorization by process area combines various types of equipment and tends to reduce the difference in cost distributions.

In terms of process area costs the annual revenue requirements for collection remain essentially constant regardless of the disposal method. The equipment is essentially the same in all cases with the exception of the vacuum producer and pumps. Base case 3 is slightly lower than base cases 1 and 2 because of lower pumping costs related to the shorter distance to the ponds. Base cases 4 and 5 have higher fly ash collection costs because of higher capital charges related to the particulate collectors and mechanical vacuum pump.

Transportation annual revenue requirements are higher for trucking to a landfill (base case 4) than they are for sluicing to a pond (base cases 1 and 2). Maintenance, labor, and to a lesser extent diesel fuel, are important cost elements in trucking. Maintenance costs are lower for sluicing than for trucking, electricity costs are lower than diesel fuel costs, and labor costs are minor. Transportation annual revenue requirements for base case 3, which uses both sluicing and trucking, are increased by costs associated with removing the ash from the ponds, particularly dredging costs. There is no large difference in transportation annual revenue requirements for dry ash, represented by base case 5, and moist ash, represented by base case 4.

Disposal site annual revenue requirements are the largest cost element in all of the disposal methods. Most of the costs in the ponding methods (base cases 1 and 2) result from the capital charges. Maintenance is the only significant direct cost. Capital charges are less dominant in landfill annual revenue requirements (base case 4) and there are substantial direct costs in labor, maintenance, and diesel fuel. Base case 3 has disposal site costs intermediate between base cases 1 and 2 and base case 4. This relationship is a result of the smaller capital charges for the smaller ponds. Labor costs for base case 3 are also lower than for base case 4 because a common landfill is used.

Water treatment and recycle is not an important cost element in any of the disposal methods. Sampling and analyses, and water recycle equipment capital charges and operation are the largest cost elements. Thus base case 2, with a mile-long return system, and base cases 4 and 5, with bottom ash water recirculation systems, have higher annual revenue requirements in this area. Base case 5 also has a substantial direct cost for sulfuric acid because of the high-calcium ash.

CASE VARIATIONS

Case variations for the five base cases were calculated to evaluate the effect of different conditions on costs. The conditions studied were trucking distance to the disposal site, ash collection rate, land cost, and percentage of ash utilization.

Trucking Distance to Disposal Site

As shown in Figure 23, trucking distance has a relatively minor effect on total capital investment. Total capital investment increases at 20,300, 13,600, and 9,200 $/mile for base cases 3 through 5 respectively. This means, for example, that an increase in trucking distance from 1 to 10 miles in base case 4 increases the total capital investment by $122,000, which is 41% of the base case capital for trucking but only 1% of capital investment for the total ash disposal system. These results are derived from the number and size of trucks required, assuming an average highway speed of 30 mph, and base case cycle times of 36, 30, and 52 minutes for base cases 3 through 5 respectively. The differences among the cases reflect a lower moisture content of the fly ash for base cases 4 and 5, and a lower ash quantity in base case 5.

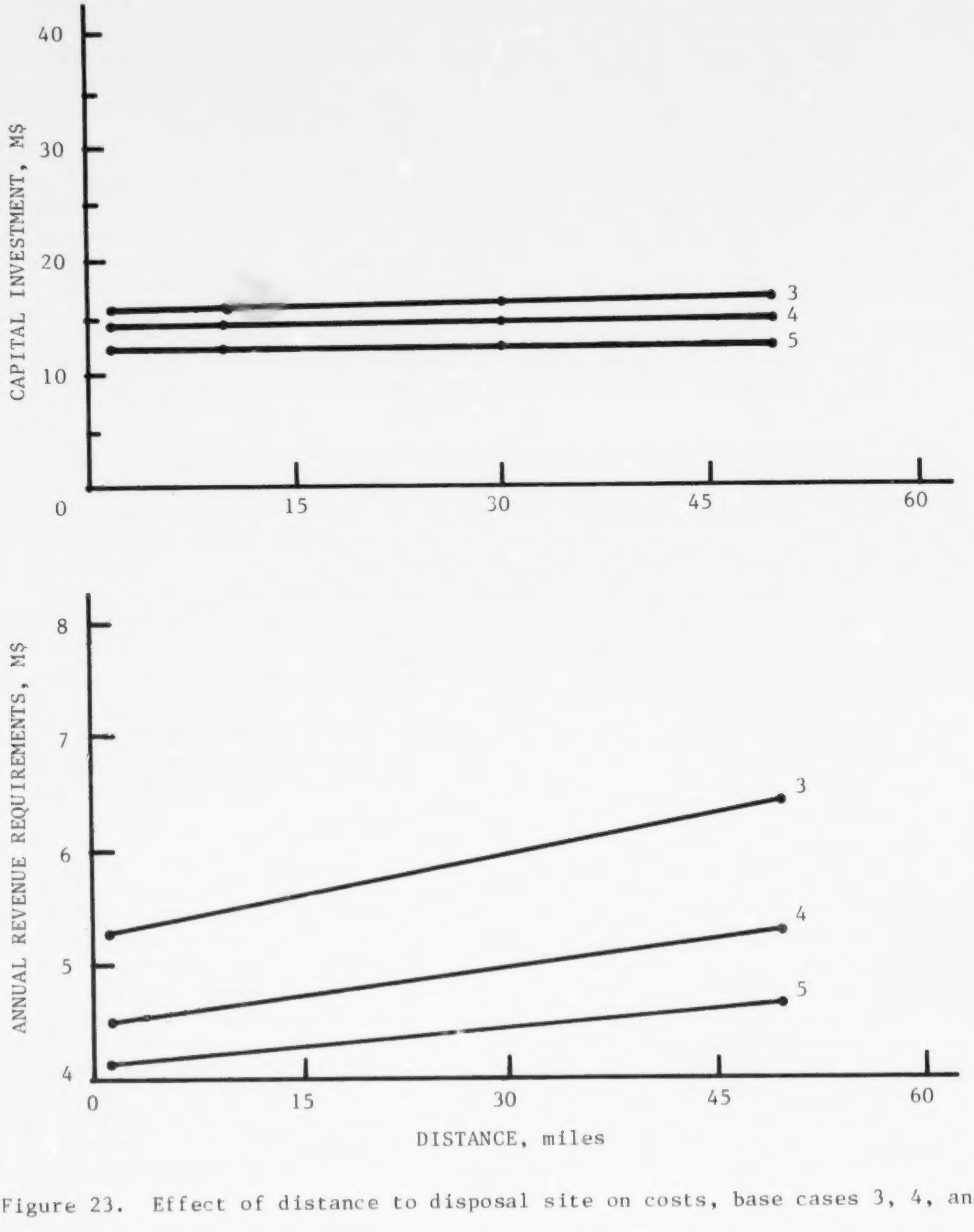

Figure 23. Effect of distance to disposal site on costs, base cases 3, 4, and 5.

Annual revenue requirements are affected by the added direct operating costs of the vehicles such as labor, fuel, and maintenance. Additional charges are incurred from higher capital charges and service overheads. Total annual revenue requirements increase constantly at rates of 23,200, 16,500, and 10,400 $/mile for base cases 3 through 5 respectively. Thus, an increase in trucking distance from 1 to 10 miles in base case 4 adds $149,000 to annual revenue requirements, which is a 40% increase for trucking but a 3% increase relative to total annual revenue requirements. As in total capital investment, these amounts take into account the different moisture contents and ash tonnages of the base cases.

Ash Collection Rate

Ash collection rate may vary with such factors as the load on the power plant, power plant heat rate, heating value of the coal, ash content of the coal, and ash collection efficiency. To evaluate the effect of ash rate on costs, capital investment and annual revenue requirements were determined at fly ash plus bottom ash collection rates totaling 47,730, 62,400, and 77,070 lb/hr. The low level is that of base case 5; the intermediate level is the collection rate for base cases 1 through 4. Figure 24 shows the results of these evaluations. It shows that both capital investment and annual revenue requirements have slightly curvilinear relationships with ash rate. The degree of curvature can be expressed as the cost-to-size exponent connecting costs for successive pairs of ash rates. The exponents are shown below for ash disposal cost relative to ash disposal rate.

Base case	47,730 to 62,400 lb/hr	62,400 to 77,070 lb/hr
Capital Investment		
1	0.75	0.75
2	0.75	0.76
3	0.73	0.70
4	0.68	0.67
5	0.66	0.70
Annual Revenue Requirements		
1	0.68	0.69
2	0.68	0.68
3	0.68	0.67
4	0.63	0.64
5	0.64	0.65

The exponents represent cost relationships in the expression cost 1 = cost 2 (rate 1/rate 2)^{exp}. The exponents for capital investment for base cases 1 and 2, using pond disposal, are 0.75, while those for base cases 4 and 5, using landfill disposal, are lower at 0.68. Base case 3 has both ponds and landfill and its exponents fall between the other pairs of cases. For annual revenue requirements, the exponents for base cases 1, 2, and 3 are virtually the same at 0.68, while base cases 4 and 5 have lower

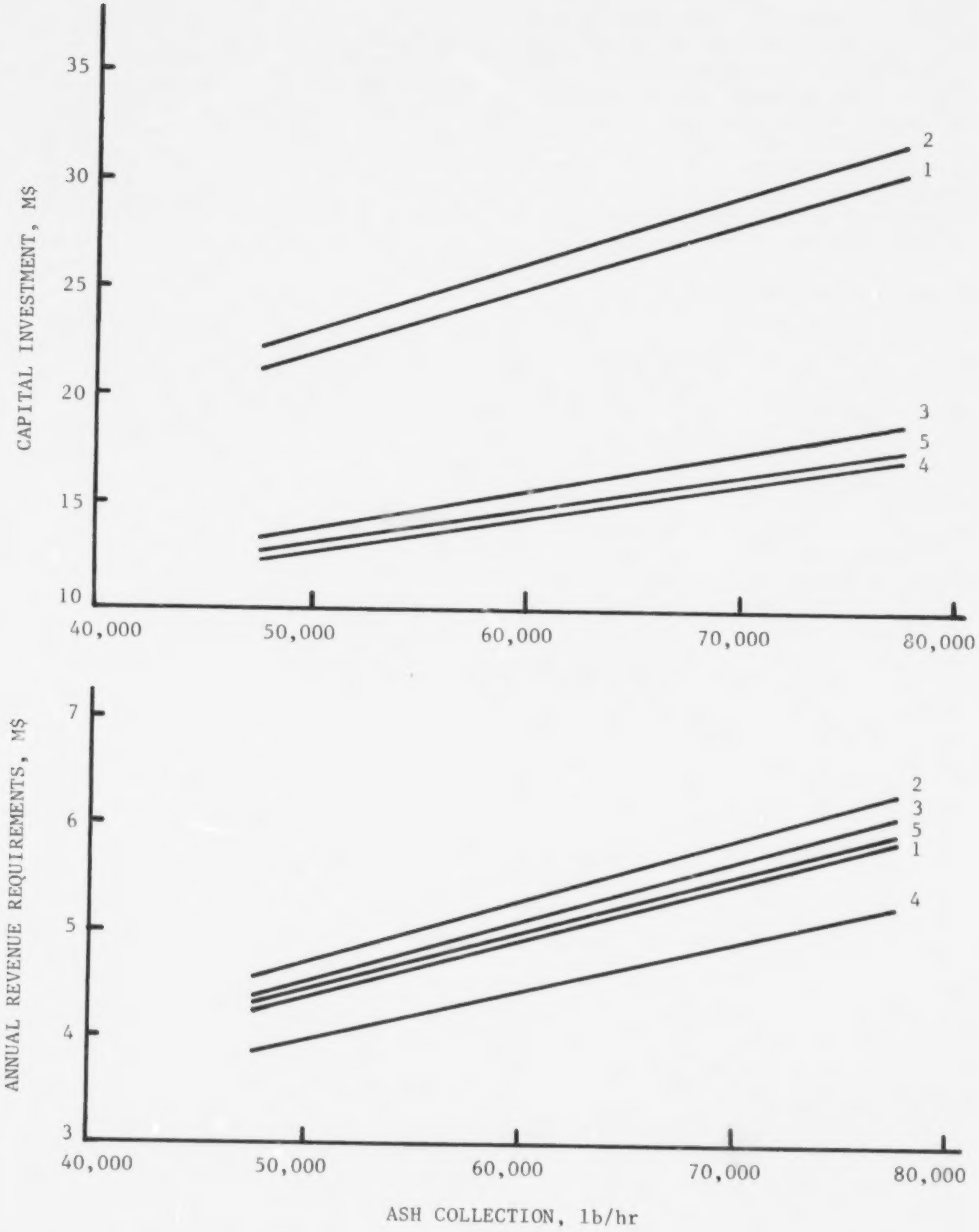

Figure 24. Effect of ash collection rate on costs, base cases 1 through 5.

exponents of 0.64. For both capital investment and annual revenue requirements, the lower exponents for cases with landfills mean that landfills have slightly greater economy of scale than do ponds.

Ponds and landfills, the dominant cost items in ash disposal, have cost variations with ash collection rate according to the size of the pond or landfill, and according to the number of ponds or landfills used. Figure 25 shows both types of variations. The ash collection rate for the life of the project translates to pond or landfill volume. For two ponds, as in base cases 1, 2, and 3 the cost-to-size exponent is 0.69 and for two landfills (base cases 4 and 5) it is 0.66. These exponents are for direct investment excluding the cost of mobile equipment for the site. The slightly lower exponent for landfills results from the previously noted greater economy of scale for landfills. Figure 25 also shows that the single landfill for base case 3 is only 87% as costly as the two landfills for base cases 4 and 5 at the same volume. This feature emphasizes the site-specific dependence of the disposal site configuration.

Land Cost

The effects of land cost and annual revenue requirements are shown in Figure 26 for land costs of $1,000, $10,000, and $15,000 per acre, as compared with the base case cost of $5,000. Land cost effects are linear and the overall cost effects are moderate. For example, increasing the cost of land from $5,000 per acre to $15,000 per acre increases base case 1 capital investment by 15% and it increases annual revenue requirements by 11%.

Ash Utilization

The effects of utilizing 25% and 50% of the ash are shown in Figure 27. Utilized ash is assumed to be removed from ponds in base cases 1 to 3 and from the fly ash silos and dewatering bins in base cases 4 and 5 at no cost to the utility. The main cost effects are in reduced trucking requirements and reduced disposal site requirements. The percentage changes in capital investment and annual revenue requirements are shown below. Utilization results in larger savings in base cases 1 and 2 than in base cases 3, 4, and 5. This difference is due to the much larger cost of ponds compared with landfills.

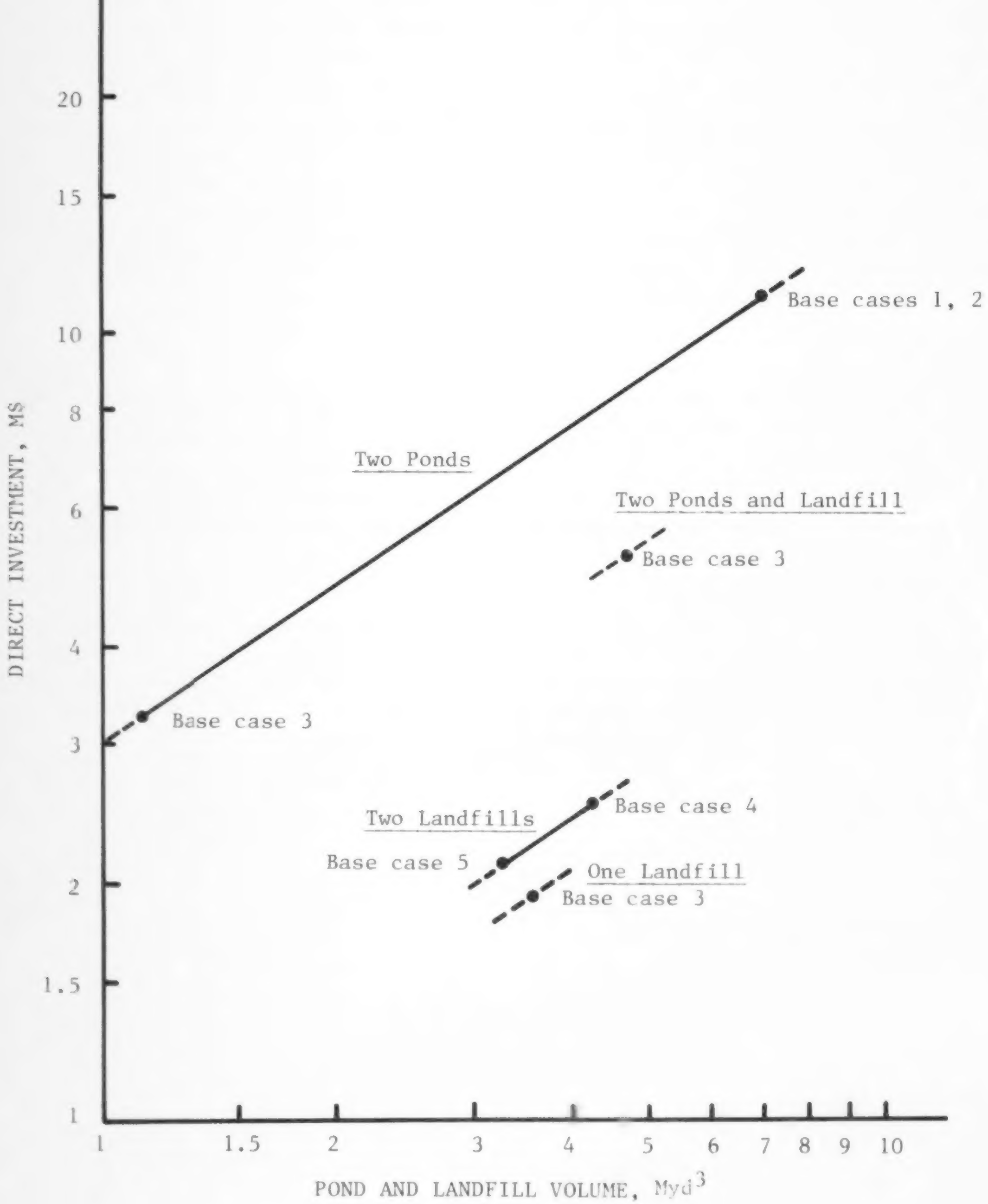

Figure 25. Effect of pond and landfill volume on direct investment.

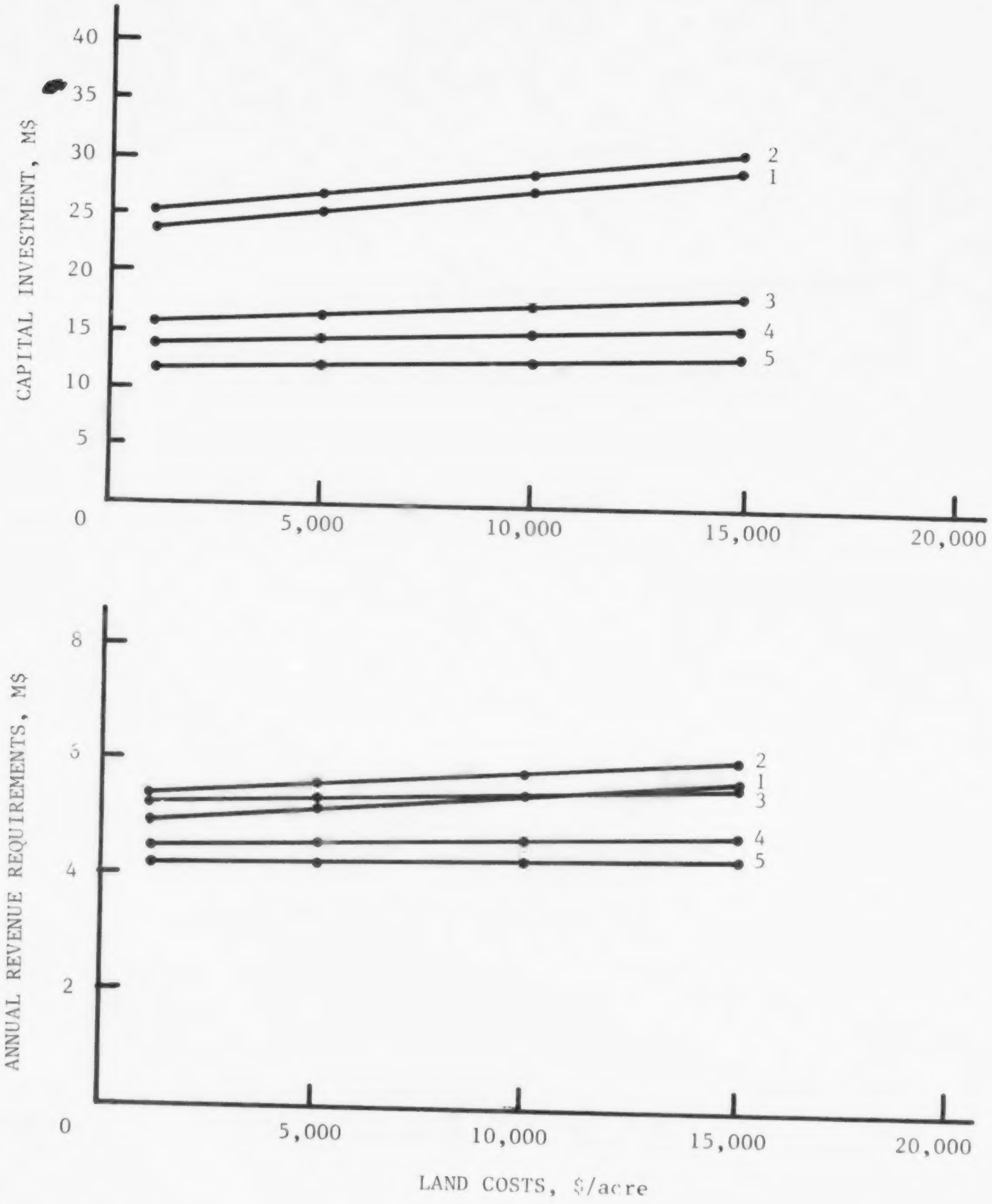

Figure 26. Effect of land costs on total costs, base cases 1 through 5.

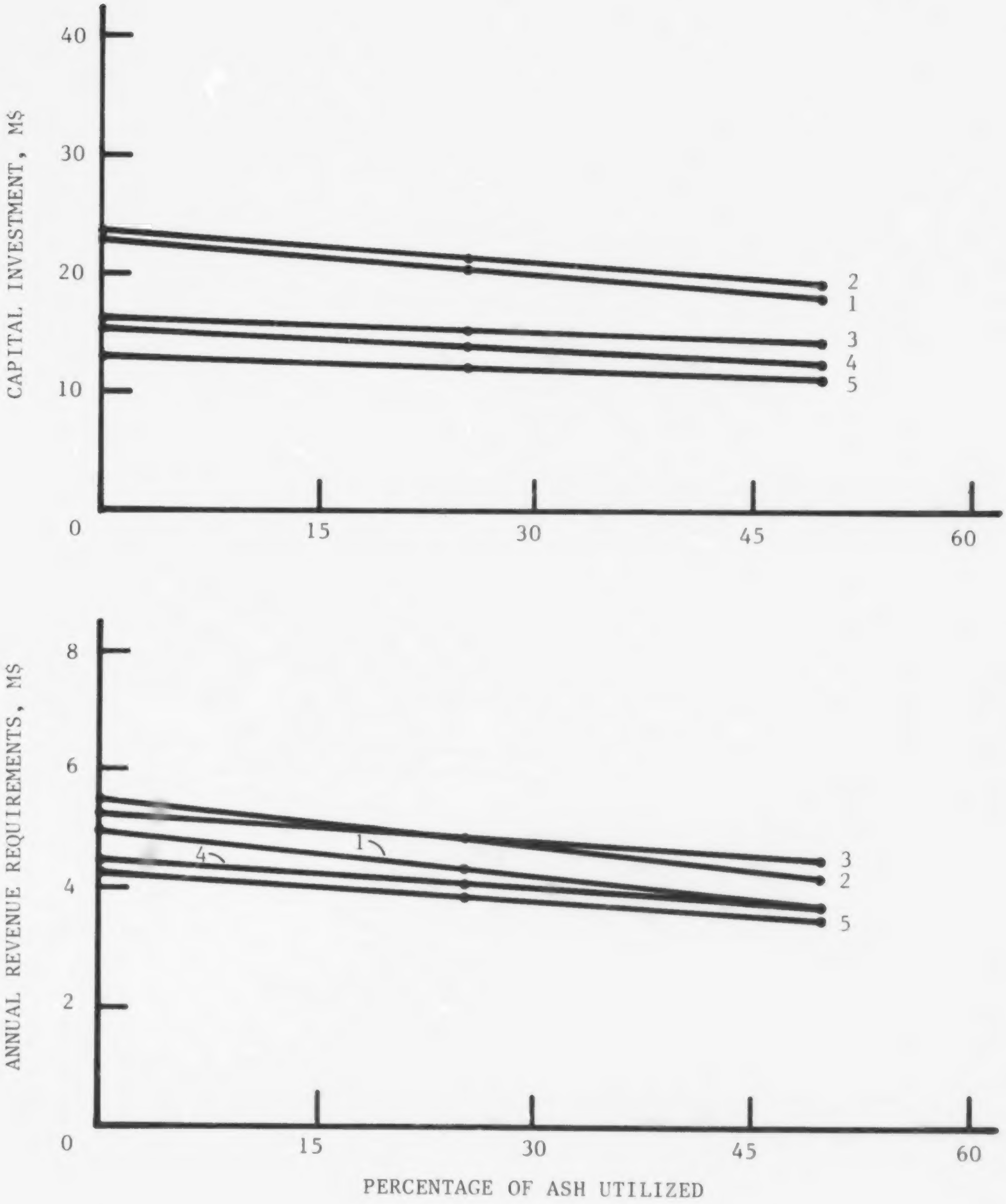

Figure 27. Effect of ash utilization on costs, base cases 1 through 5.

Percentage utilization		Capital investment percentage decrease	Annual revenue requirements percentage decrease
Base case 1:	25	14	12
	50	30	26
Base case 2:	25	14	11
	50	29	25
Base case 3:	25	10	9
	50	17	18
Base case 4:	25	9	9
	50	16	18
Base case 5:	25	11	10
	50	16	18

COMPARISON WITH TVA ASH DISPOSAL COSTS

Direct comparisons of conceptual design costs with actual costs of operating systems are frequently difficult to make because of disparate design and economic bases. This has been most apparent in comparisons of FGD costs from different sources (93, 94) where the difficulties are compounded by the relative immaturity of the technology. Ash collection, and to a lesser extent disposal, may be regarded as a more developed technology than FGD. Nevertheless, many of the same difficulties exist. In particular, site-specific conditions of actual installations such as size, ash production rates, and environmental constraints must usually be accounted for. Accounting methods may also differ, as well as the degree to which costs are identified and isolated (particularly operating labor and maintenance). As has been discussed, ash transportation distance, the configuration of the transportation path, and the disposal site itself are highly site specific. It is also necessary, of course, to use the same cost basis in comparing conceptual design costs (usually projected into the future) with actual costs (usually for a period one or more years in the past).

It is possible, however, to compare certain aspects of the costs developed in this study with actual ash disposal costs at TVA coal-fired power plants. There are 12 coal-fired power plants in the TVA system, all of which presently dispose of ash by sluicing to permanent ponds with once-through condenser cooling water from a river, similar to the base case 1 process of this study. The pond effluents have been described in a previous study (74). Eight of the TVA plants were selected for cost comparisons with the base case 1 conceptual design. The others have cyclone or wet-bottom furnaces or have disposal site expansion costs that cannot be differentiated from the usual operating costs. The eight plants selected have dry-bottom pulverized-coal-fired furnaces burning bituminous coal. They were constructed in the period 1951 to 1973. The average station capacity is 1,600 MW and the average unit capacity is 260 MW. In 1978 the average yearly ash production was 563,000 tons per plant. (In comparison, base case 1 represents a 500-MW power unit producing 171,600 tons of ash per year.) The bottom ash is typically sluiced from the hoppers through clinker grinders and pumped through steel pipelines with centrifugal pumps. Fly ash is typically removed from the flue gas with ESP's or mechanical collectors and collected with vacuum systems using water ejectors. It is sluiced to the ponds through steel pipes, either separately or combined with the bottom ash. The onsite ponds differ in size, configuration, and construction technique and are situated from a few hundred feet to over one mile from the power plants.

Comparisons of base case 1 direct capital investment can be made with the installed costs of ash disposal equipment for two power units at two TVA plants constructed in 1963 and 1965. Indirect costs cannot be readily compared because of differences in accounting and financial practices.

Computed by the same method, the total capital investments would have the same relationships as the direct costs, however. Similarly, the base case 1 operating and maintenance costs are compared with the TVA operating and maintenance costs. In this comparison costs for all eight of the TVA plants are used. The TVA costs vary among plants because of site-specific conditions so the average of the costs at the eight plants is used as the basis of comparison.

Several adjustments are made in the cost data to provide the same basis of comparison. Since TVA power plants were constructed at different times, their equipment costs are projected to 1982 for comparison with the base case 1 capital costs. The TVA costs are also adjusted for size, pipeline length, and other factors as discussed below. Pond site costs are excluded from the equipment cost comparison because of the differences in design concepts and the highly variable site-specific nature of the TVA ponds. The common time basis for operating and maintenance costs was obtained by adjusting the TVA 1978 average costs to 1984 for comparison with the base case 1 projected 1984 operating and maintenance costs.

EQUIPMENT COST COMPARISONS

The costs of installed ash disposal equipment at the two TVA power plants used and the nature of the adjustments needed for comparison with base case 1 are shown in Tables 32 and 33. The TVA costs represent materials, installation labor, and supporting equipment. The ESP hopper costs are excluded from the base case 1 costs because they are not differentiated in the TVA ESP costs. The TVA cost adjustments consist of: (1) an increase in the bottom ash hopper capacity from 8 to 12 hours, (2) an adjustment in the pipelines to a one-mile length, basalt lining, and spare provisions, (3) a size factor based on a cost-to-size exponent of 0.8, and (4) an inflation factor.

Results of the adjusted ash disposal investment costs for plants A and B are summarized and compared with the conceptual-design costs in Table 34. For the total ash disposal system, the conceptual-design cost of base case 1 is 10% higher than that of plant A and 5% higher that that of plant B. Relative to both plants, the base case costs are high for bottom ash disposal and slightly low for fly ash disposal. Incomplete allocations between the bottom ash and fly ash systems could account for this.

OPERATING AND MAINTENANCE COST COMPARISON

The operating and maintenance costs (excluding electricity) for ash disposal from 1970 to 1978 at the eight TVA plants are shown in Figure 28. The 1978 average is projected to 1984 using the cost indexes in the premises. The base case 1 operating and maintenance cost is also shown using the 1984 cost developed in this study and as an adjusted cost based on an ash production rate equivalent to the TVA rate.

The TVA costs comprise the operating labor and the maintenance labor and materials for removal of ash from the hoppers, sluicing to the ponds, pond

TABLE 32. INSTALLED COST OF ASH DISPOSAL SYSTEMS AT TVA POWER PLANT A

	TVA accounted cost, k$ (1963)	Adjustments to meet base-case conditions		Adjusted cost, k$ (1982)
Bottom Ash Disposal System				
Collecting and Handling System				
Ash hopper assembly (8-hour storage capacity, clinker grinders, etc.) and associated handling equipment (pumps, motors, piping, valves, and control equipment)	290.2	Addition for 12-hour storage capacity on hopper cost of k$ 139.2	53.3	
		Unit size and inflation factor[a]	2.713	932
Disposal Piping				
1,500-foot-long slurry pipelines (carbon steel, extra strong) with fittings, and supports	58.0	Bottom ash allocation of pipeline cost, 20% of k$ 58.0	11.6	
		Pipeline extension to 1 mile	29.2	
Trench under powerhouse for bottom ash and fly ash piping	71.8	Addition for basalt-lined quality	122.9	
		Share of 1-mile, carbon-steel spare pipeline	16.1	
		Bottom ash allocation of trench cost, 20% of k$ 71.8	14.4	
		Unit size and inflation factor[a]	2.713	527
Sluice Water Supply System				
Pumps, motors, piping, fittings, and valves for bottom ash and fly ash systems	98.6	Bottom ash allocation, 20%	19.7	
		Unit size and inflation factor[a]	2.713	54
Total, bottom ash disposal system				1,513
Fly Ash Disposal System				
Handling System				
Vacuum pneumatic system of valves, piping, and control equipment for handling ash from hoppers on air preheaters, primary air heater, gas outlet ducts and ESP, and delivery to combined ash slurry pipelines; excludes ESP and hoppers	123.6	Hopper insulation accounted with ESP which is excluded from ash disposal comparison	44.9	
		Unit size and inflation factor[a]	2.713	457
Disposal Piping	-			
Accounted in cost of bottom ash disposal piping and trench		Fly ash allocation of pipeline cost, 80% of k$ 58.0	46.4	
		Pipeline extension to 1 mile	116.9	
		Share of 1-mile carbon-steel spare pipeline	64.4	
		Fly ash allocation of trench cost, 80% of k$ 71.8	57.4	
		Unit size and inflation factor[a]	2.713	773
Sluice Water Supply System	-			
Accounted in cost of bottom ash sluice water supply system		Fly ash allocation, 80% of k$ 98.6	78.9	
		Unit size and inflation factor[a]	2.713	214
Total, fly ash disposal system				1,444
Total, ash disposal systems	642.2			2,957

a. Unit size factor of 0.927 and inflation factor of 2.927.

TABLE 33. INSTALLED COST OF ASH DISPOSAL SYSTEMS AT TVA POWER PLANT B

	TVA accounted cost, k$ (1965)	Adjustments to meet base-case conditions		Adjusted cost, k$ (1982)
Bottom Ash Disposal System				
Collecting and Handling System				
Ash hopper assembly (50-ton capacity, clinker grinders, etc.) and associated handling equipment (pumps, motors, piping, valves, and control equipment)	323.9	Addition for 12-hour storage capacity on hopper cost of k$ 214.4	82.1	
		Unit size and inflation factor[a]	1.722	699
Disposal Piping				
3,240-foot-long slurry pipelines (carbon steel, extra strong) with fittings, and supports	244.8	Bottom ash allocation of pipeline cost, 20% of k$ 244.8	49.0	
		Pipeline extension to 1 mile	30.8	
Trench under powerhouse for bottom ash and fly ash piping	159.7	Addition for basalt-lined quality	240.2	
		Bottom ash allocation of trench cost, 20% of k$ 159.7	31.9	
		Unit size and inflation factor[a]	1.722	606
Sluice Water Supply System				
Pumps, motors, piping, fittings, and valves for bottom ash and fly ash systems	312.0	Bottom ash allocation, 20%	62.4	
		Unit size and inflation factor[a]	1.722	107
Total, bottom ash disposal system				1,412
Fly Ash Disposal System				
Handling System				
Vacuum pneumatic system of valves, piping, and control equipment for handling ash from economizers and ESP, and delivery to combined ash slurry pipelines; excludes ESP and hoppers	175.3	Hopper insulation accounted with ESP which is excluded from ash disposal comparison	113.2	
		Unit size and inflation factor[a]	1.722	497
Disposal Piping				
Accounted in cost of bottom ash disposal piping		Fly ash allocation of pipeline cost, 80% of k$ 244.8	195.8	
		Pipeline extension to 1 mile	123.3	
		Fly ash allocation of trench cost, 80% of k$ 159.7	128.8	
		Unit size and inflation factor[a]	1.722	771
Sluice Water Supply System				
Accounted in cost of bottom ash sluice water supply system		Fly ash allocation, 80% of k$ 312.0	249.6	
		Unit size and inflation factor[a]	1.722	430
Total, fly ash disposal system				1,698
Total, ash disposal systems	1,215.7			3,110

a. Unit size factor of 0.598 and inflation factor of 2.877.

TABLE 34. COMPARISON OF BASE CASE 1 WITH TVA INSTALLED COSTS OF ASH DISPOSAL SYSTEMS

	Bottom ash disposal system		Fly ash disposal system		Total ash disposal systems	
	k$ (1982)	Base case difference, %	k$ (1982)	Base case difference, %	k$ (1982)	Base case difference, %
Base case 1	1,772	-	1,482[a]	-	3,254	-
TVA plant A[b]	1,513	+17	1,444	+ 3	2,957	+10
TVA plant B[c]	1,412	+25	1,698	-13	3,110	+ 5

a. Excluding fly ash hoppers.
b. Adjusted as shown in Table 32.
c. Adjusted as shown in Table 33.

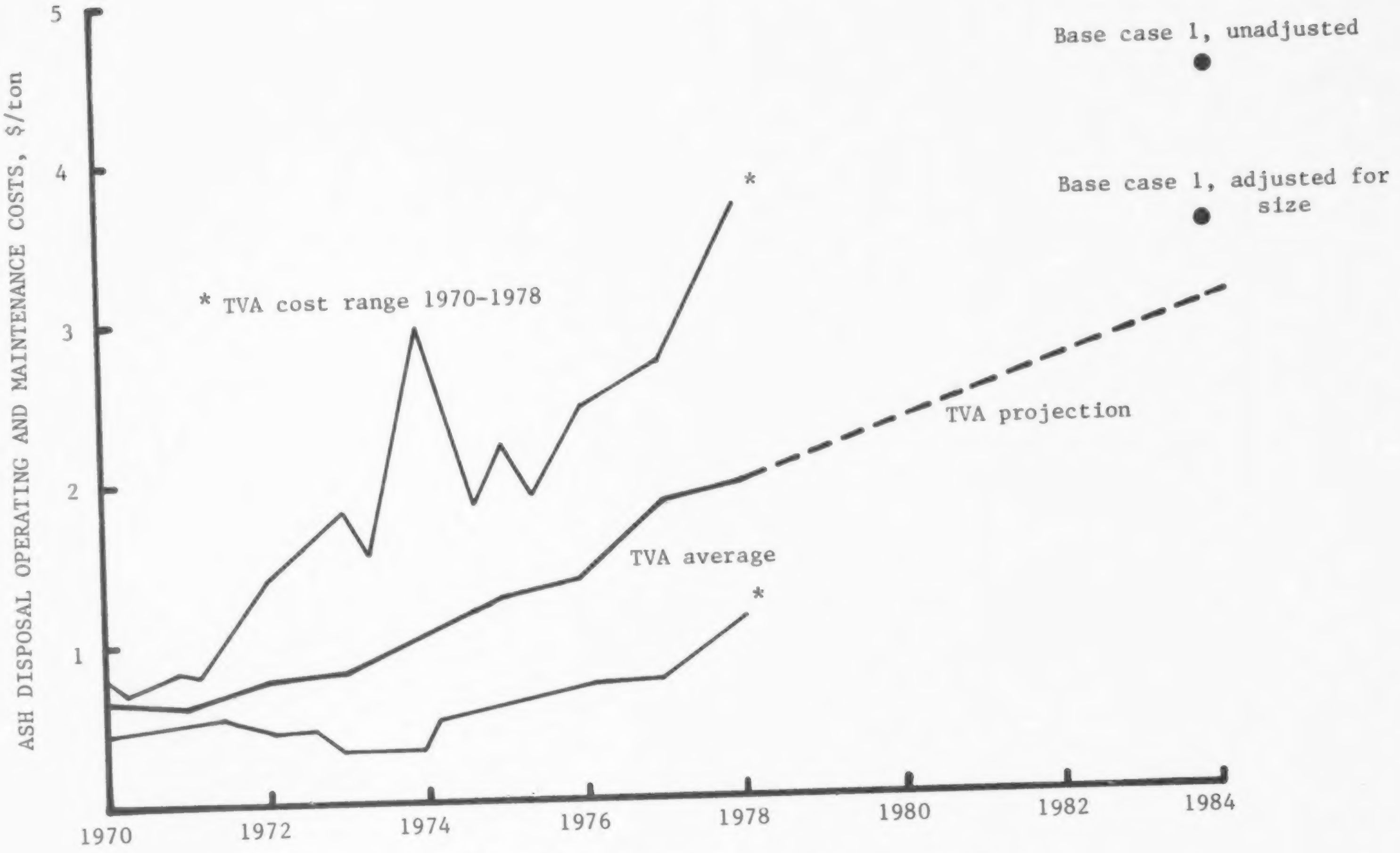

Figure 28. TVA and base case 1 operating and maintenance ash disposal costs.

maintenance, and treatment and control of the discharge water. For each plant, the costs are expressed as annual dollars per ton of ash. In 1978 the average TVA ash production rate per plant was 562,500 tons of ash, producing an average operating and maintenance cost of $1.95 per ton. Projected to 1984 the cost is $3.07 per ton.

Base case 1 operating and maintenance costs are obtained, on a comparative basis, from annual revenue requirements as shown in Table 35. Here, the total direct costs comprise only $4.82/ton of ash of the total annual revenue requirements of $29.63/ton of ash. This perspective illustrates that plant-based direct costs are only 16% of the total amount. Base case 1 operating and maintenance costs, excluding electricity, are $766,800, or $4.47 per ton in 1984 dollars based on 171,600 tons per year of ash. This cost is based on an ash production rate that is 31% of the TVA average rate. Comparison of the ash collection and slurry pipeline systems indicates that 0.79 is an appropriate size correction factor (not an exponent). Applying this correction, the base case 1 costs become $3.53 per ton in 1984 dollars.

Design differences other than plant size and ash tonnage lead to small or offsetting differences in operation and maintenance cost. For example, a reduction in length of slurry pipeline from 1 mile to 1/2 mile would lower pipeline maintenance by $0.20 per ton of ash but the combination of greater ash dilution and higher slurry velocities in the TVA pipelines appears to increase the pipeline size, and hence maintenance cost, by a similar amount.

At $3.53 per ton of ash, the base case 1 cost for operation and maintenance is 15% higher than the 1984 TVA cost of $3.08 per ton of ash. A part of this difference is due to the provisions in base case 1 for additional environmental protection.

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TABLE 35. BASE CASE 1 OPERATING AND MAINTENANCE COSTS

COMPARATIVE BASIS

	Annual revenue requirements, 1984 $		Operations and maintenance, comparative basis, 1984 $
	k$	$/ton	$/ton
Direct Costs			
Conversion costs			
Operating labor	206.3		
Process reagents	3.6		
Utilities			
Water	6.9		
Electricity	61.1		
Maintenance			
Process	287.0		
Pond	221.0		
Sampling and analysis	42.0		
Total direct costs	827.9	4.82	
Total direct costs excluding electricity	766.8	4.47	3.53
Indirect Costs			
Plant and administrative overheads	456.0		
Levelized capital charges	3,801.4		
Total indirect costs	4,257.4	24.81	
Total first-year annual revenue requirements	5,035.3	29.63	

Basis: Ash rate, 171,600 tons/year. Plant cost indexes, 218.8 in 1978, 344.9 in 1984.

COMPARISONS AMONG ASH DISPOSAL STUDIES

Results of this study can be compared with those of published reports only to the extent that comparability exists among the disposal systems evaluated and among the methods used. Rarely are comparisons of actual cost possible for total ash disposal systems because of the varying design and economic premises found in this highly site-specific subject.

The disposal rate and site capacity are determined by coal properties and boiler features, operating schedules of the boiler and ash removal systems, and duration of plant life. Choice of ash handling and transportation equipment is influenced by factors such as the nature of the ash, the altitude of the site, the transportation distance and terrain, and by the type of disposal site. The largest contributor to ash disposal costs, the disposal site, reflects the characteristics of the ash, terrain, land availability, soil conditions, and environmental constraints.

Typical combinations of these variables which serve as design premises for three separate studies are shown in Table 36. Even without the intricacies of pond and landfill designs, the listing shows the breadth of conditions encountered. Most impressive are the lifetime tonnages of ash, which range from 2.8 to 61 million tons, and the lifetime volumes of ash, which range from 2.6 to 56 million yd^3 for landfill disposal. These divergent amounts cannot safely be reduced to a common basis by the application of cost-to-size scaling factors unless the factors are accurately known for the particular designs.

The economic premises also differ among the studies, and when inflation, discounting, and levelization factors are used, the results are greatly influenced by the factors chosen. It is extremely difficult to compare ash disposal costs which are based on different premises and are expressed on different bases such as (1) first-year operating costs, (2) levelized operating costs, (3) life-of-project costs, and (4) present worth life-of-project costs. The purposes, methodologies, and expression of results among these studies explain why they can validly differ in the type of ash disposal systems used and in qualitative results.

This study includes all areas of ash handling and disposal from collection hoppers through disposal site and effluent treatment. Its disposal site designs are based on the RCRA nonhazardous guidelines. It emphasizes comparisons among modules of ash collection, handling, and disposal, including wet transportation to ponds and dry transportation to landfills, but its scope does not include all forms of ash transportation or variations in site topography. The capital investments are based on full and nondiscounted

TABLE 36. COMPARISON OF PREMISES AND COSTS AMONG ASH DISPOSAL STUDIES

	This study (EPA)		Bahor-Ogle (EPA)		GAI Consultants (EPRI)	
Design Premises						
Plant location	North Central U.S.		Southeastern U.S.		Midwestern U.S.	
Plant life, yr	30		35		30	
Boiler type	P-C dry bottom		P-C dry bottom		-	
Generating capacity, MW	500		2,600		500	
Plant heat rate, Btu/kWh	9,500		10,000		9,000	
Capacity factor, %, hourly	100		80			
Capacity factor, %, yearly	63		80		70 1st year 48.5 average	
Coal type	Bituminous		Subbituminous			
Coal heating value, Btu/lb	11,700		10,500		10,500	
Coal ash, as fired, %	15.1		20		12.8	
Ash to fly ash, %	80		80		80	
Coal sulfur, as fired, %	3.36		-		-	
Sulfur to ash, %	8		-		-	
Ash utilization	0		0		All bottom ash	
Ash to disposal, tons/hr	31		198			
Ash to disposal, tons/yr	171,000		1,735,000		94,600	
Ash to disposal, tons/life	5,120,000		60,736,000		2,840,000	
Ash to disposal, tons/MWyr	0.062		0.095		0.045	
Type of disposal site detailed:	Pond	Landfill	Pond	Landfill	Pond	Landfill
Solids in slurry, %	7.7	-	10	-	5	-
Slurry water recycle	No	-	Yes	-	Yes	-
Distance to disposal site, mile	1	1	1	1	1	1
Terrain	Level	Level	Narrow valley	Narrow valley	Level	Level
Ash bulk density, lb/ft^3	55	90	43	83	60	80
Ash volume, Myd^3	6,9	4.2	104	56	3.5	2.6
Land area, acre	390	142	639	460	107	40
Depth of fill, ft	14 or 17	20 to 80	-	200	25	50
Liner	Clay	Clay	Synthetic	Synthetic		
Groundwater monitoring wells	4	4	None	None		
Stormwater treatment	Yes	Yes	No	No		
Security fence	Yes	Yes	No	No		
Closure, revegetation	Yes	Yes	Yes	Yes	Yes	Yes
Economic Premises						
Construction year	1982		1980		1979	
Startup year	1984				1980	
Areas costed	Hoppers, collection, transportation, disposal		Collection, transportation, disposal		Transportation, disposal	
Capitalization of site construction	100%		100%		100%	1/30
Capitalization of closure, revegetation	100%				At present worth	0
Land cost, $/acre	5,000		1,500		5,000	
Final Costs						
Total capital investment, k$	25,860	14,750			7,900	522
Total system cost, k$			1,083,000	1,499,000		
Present worth cost, k$			133,000	168,000		
First-year annual revenue requirements, k$	5,085	4,555				
Levelized annual revenue requirements, k$	6,223	6,669			2,260	925
First-year annual revenue requirements, $/ton dry ash	29.63	26.54				
Levelized annual revenue requirements, $/ton dry ash	36.26	38.86			23.86	9.78

capitalization of the life-of-project disposal sites and its operating and maintenance costs are given on first-year and levelized bases. Detailed costs are shown in each base case.

A recent study of wet versus dry ash disposal systems by Bahor and Ogle (95) stresses disposal sites. It does not include collection hoppers, uses an average cost for ash collection, and shows results for four methods of transportation and four profiles of valley sites, each with and without liners. Site designs follow implied State codes somewhat less restrictive than RCRA requirements. The derivation of results is shown for only two specific cases but end results are tabulated for 280 combinations of plant capacity, transportation, site, and liner. The capital investment and operating-maintenance costs are presented in two forms, present worth and total system cost. Present worth is the initial capital investment plus the present worth of inflated and discounted operating-maintenance costs for the life of the project. Total system cost is a weighted cost of capital plus operating-maintenance costs inflated during the life of the project. An 11% discount rate and an 8.5% inflation rate is used, compared with 10% and 6% for this study.

The cost estimating section of the GAI EPRI study (75) emphasizes economic methodology, with graphical and computational derivation of the principal variants in ash disposal. However, illustrative economics are provided for a pond and a landfill case utilizing site costs from a prior sludge disposal study. Capital investment and annual revenue requirements are based on EPRI premises (90). Two effects of time are taken into account. Since the cost of pond closure and revegetation occurs at the end of the project, its initial capitalization is expressed at present worth. Also, since the landfill is built over the life of the project, its initial capitalization is taken at 1/30 of its total cost. These conventions reduce the pond and landfill capital investments proportionately, as compared with 100% capitalization in the current study.

The preceding illustrations show that the disposal systems and their economic evaluation vary widely from study to study and in most cases comparability of specific cost results can only be established by recalculation of the results. On the other hand, a report may have qualitative conclusions based on comparability within the study and such conclusions are subject to comparison between reports. Such a comparison can be made between this study and the stated conclusions of Bahor and Ogle. In this 1981 economic analysis of pond and landfill ash disposal systems, Bahor and Ogle examined different types of disposal sites and concluded that site topography was the primary influence on the economic selection of an ash disposal system. Partly because of that study, the present conceptual design assumes level disposal sites and does not address topography.

Bahor and Ogle state that the method of economic analysis is not a primary factor in selection of an ash disposal system, that is, in determining a least-cost option. This assumes that the method is compatible with the actual economics of the installation and operation of the system, of course, and pertains only to comparisons within the same economic method. As discussed above, qualitative comparisons of economic results derived using different methods cannot normally be made without adjustments frequently of such a nature as to destroy the integrity of the adjusted results. In contrast, qualitative results should be comparable, and in many cases synergetic, providing in the comparison conclusions unattainable from the individual studies.

In the present study landfill disposal has lower capital investment and annual revenue requirements than pond disposal. Pond construction costs, based on a level site requiring a designed pond with wholly enclosing dikes, are the determinant factor in the cost relationships for both capital investment and (as capital charges) for annual revenue requirements. Although not addressed in quantitative terms because of its site-specific nature, the use of natural landforms to reduce dike requirements would have a major effect on cost relationships. Bahor and Ogle address this situation in greater detail, providing quantitative data to support the conclusion. In general, landfill disposal is the least cost alternative for flat areas whereas pond disposal is the least cost alternative for valley disposal. In the GAI study, which assumes a level site, this conclusion is supported by an even greater difference in costs, due in large part to the smaller ash quantities and relatively lower landfill construction costs. Bahor and Ogle use generalized in-plant handling costs (95, p. 68) which differ considerably between wet and dry systems. The difference is sufficient in some cases to influence the relationship of overall pond and landfill disposal costs. In this study ash collection and handling costs are subordinate to disposal site costs but constitute an important element in overall costs. Different systems are defined in detail. Both studies thus provide insight into the overall relationship of the various ash collection and disposal costs. These relationships are not specifically addressed in the GAI study.

Overall, comparison of these studies reveals variations in the disposal systems used, in the economic structure of the evaluations, and in the focus of purpose that is in many cases complementary. The conclusions are, however, in general agreement.

CONCLUSIONS

The most common current method of utility ash disposal is sluicing to a permanent pond with no water recycle. The capital investment for this method of disposal for a 500-MW power unit burning coal with 15.1% ash with a pond one mile away is 52 $/kW (1982$). Annual revenue requirements for ash disposal for the same plant, operating 5,500 hr/yr, are 1.85 mills/kWh (1984$). Reuse of sluicing water, including treatment to prevent scaling, increases the capital investment by about 2 $/kW and annual revenue requirements by about 0.13 mill/kWh.

Landfill disposal (consisting of dewatering the bottom ash and dry collection of the fly ash followed by trucking of the ash one mile to a managed landfill) has a capital investment of 30 $/kW and annual revenue requirements of 1.66 mills/kWh for the same power unit conditions, which is less costly than ponding.

A combination process using temporary ponding in 5-year-capacity ponds followed by removal of the ash to a landfill has a capital investment of 32 $/kW and annual revenue requirements of 1.91 mills/kWh. There is no apparent economic advantage in using temporary ponds with new power plants.

The costs for disposal of a self-hardening (high-calcium) ash are slightly higher in cost per ton of ash than disposal costs for nonhardening ash. The main cost differences are slightly higher truck costs for covered beds and moisturizers, addition of compaction water at the landfill, and slightly higher bottom ash water treatment costs. In many practical situations these would be more than offset by the lower ash content of many high-calcium coals.

In all cases, disposal site costs are the largest cost element in both capital investment and annual revenue requirements. In pond-disposal processes pond cost constitutes two-thirds of the capital investment. In comparison, landfill capital investment constitutes about one-third of the total capital investment in landfill disposal processes. In both cases, construction functions involving earthmoving are the major cost factors. The capital investment contribution to annual revenue requirements as capital charges is the largest factor in total annual revenue requirements.

Trucking distance has little effect on capital investment because trucks are a minor element in capital investment. Distance increases annual revenue requirements moderately because of increased operating costs and labor requirements. Moisture content has an important effect on trucking costs.

Ash utilization has a significant effect on costs, particularly for pond disposal processes. Fifty percent utilization reduces capital investment and annual revenue requirements about one-fourth for pond disposal and one-sixth for landfill disposal. For these cost savings to be fully realized, however, the disposal site size must be designed for the reduced quantity of ash.

Although the design is considerably different, the costs for ash collection do not differ greatly whether the ash is sluiced directly to ponds or the bottom ash is dewatered and the fly ash is collected dry for trucking to landfills. The capital investment for truck transportation (including storage silos) is, however, about one-third higher than the capital investment for sluicing and the annual revenue requirements for trucking are about twice as high as those for sluicing.

Hopper costs are a major element in overall ash disposal capital investment. Changes in the size or design of the hoppers will significantly affect disposal costs.

Capital investment and annual revenue requirements for bottom ash disposal are about twice as high as those for fly ash disposal in terms of cost per ton of ash, primarily because of the economy of scale in equipment and disposal site costs for the higher volume of fly ash.

Base case 1 direct capital investment, excluding ponds, operating and maintenance costs, and electricity, are in general agreement with selected equivalent TVA costs when the TVA costs are adjusted for unit size and cost-basis year.

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APPENDIX A

BASE CASE CAPITAL INVESTMENT AND ANNUAL REVENUE REQUIREMENTS

TABLE A-1. CAPITAL INVESTMENT - BASE CASE 1,

DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Investment, 1982 k$		
	Fly ash	Bottom ash	Total
Direct Investment			
Ash collection	1,193	821	2,014
Ash transportation to disposal site	915	951	1,866
Ash disposal site	8,509	2,127	10,636
Water treatment and recycle	54	14	68
Total process areas	10,671	3,913	14,584
Services, utilities, and miscellaneous	427	157	584
Total direct investment	11,098	4,070	15,168
Indirect Investment			
Engineering design and supervision	312	155	467
Architect and engineering contractor	158	77	234
Construction expense	933	363	1,296
Contractor fees	577	222	799
Total indirect investment	1,979	817	2,796
Contingency	1,307	489	1,796
Total fixed investment	14,384	5,376	19,760
Other Capital Investment			
Allowance for startup and modifications	248	204	452
Interest during construction	2,245	838	3,083
Total depreciable investment	16,877	6,418	23,295
Land	1,560	390	1,950
Working capital	444	171	615
Total capital investment	18,881	6,979	25,860
$/kW	37.76	13.96	51.72

Basis: New, 500-MW, midwestern, dry-bottom, pulverized-coal-fired boiler with a 30-year, 165,000-hour life and a 9,500 Btu/kWh heat rate. Eastern low-calcium coal with a 11,700 Btu/lb heating value, 3.36% sulfur, 15.1% ash, as fired, producing 62,400 lb/hr of ash as 80% fly ash and 20% bottom ash. Fly ash removal to meet 0.03 lb/MBtu NSPS. Separate 30-year fly ash and bottom ash ponds one mile from the power plant based on 55 lb/ft^3 dry bulk density of settled ash, 165,000 hours of operation, and no ash utilization. Costs are projected to mid-1982 and include bottom, economizer, air heater, and ESP ash hoppers and all subsequent equipment and facilities.

TABLE A-2. ANNUAL REVENUE REQUIREMENTS

BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

		Fly ash, 1984 k$		Bottom ash, 1984 k$		Total, 1984 k$
Annual revenue category	Cost, $/unit	Annual quantity	Annual revenue requirements	Annual quantity	Annual revenue requirements	Annual revenue requirements
Direct Costs						
Conversion costs						
Operating labor	15.00/man-hr	7,040 man-hr	105.6	6,710 man-hr	100.7	206.3
Process reagents						
H_2SO_4 (100% equivalent)	65.00/ton	44 tons	2.9	11 tons	0.7	3.6
Utilities						
Water	0.014/kgal	393,200 kgal	5.5	98,310 kgal	1.4	6.9
Electricity	0.037/kWh	1,135,100 kWh	42.0	517,300 kWh	19.1	61.1
Maintenance						
Process			161.2		125.8	287.0
Pond			176.8		44.2	221.0
Sampling and analysis	21.00/man-hr	1,000 man-hr	21.0	1,000 man-hr	21.0	42.0
Total direct costs			515.0		312.9	827.9
Indirect Costs						
Plant and administrative overheads (60% of conversion costs less utilities)			280.5		175.5	456.0
Total first-year operating and maintenance costs			795.5		488.4	1,283.9
Levelized capital charges (14.7% of total capital investment)			2,775.5		1,025.9	3,801.4
Total first-year annual revenue requirements			3,571.0		1,514.3	5,085.3
Levelized first-year operating and maintenance costs (1.886 x first-year operating and maintenance costs)			1,500.3		921.1	2,421.4
Levelized capital charges (14.7% of total capital investment)			2,775.5		1,025.9	3,801.4
Total levelized annual revenue requirements			4,275.8		1,947.0	6,222.8
Equivalent unit revenue requirements						
Unit first-year revenue requirements						
k$			3,571		1,514	5,085
Mills/kWh			1.30		0.55	1.85
$/ton dry ash			26.01		44.12	29.63
Unit levelized revenue requirements						
k$			4,276		1,947	6,223
Mills/kWh			1.55		0.71	2.26
$/ton dry ash			31.15		56.73	36.26

Basis: One-year, 5,500-hour full-load operation of the system described in the capital investment summary; costs projected to mid-1984.

TABLE A-3. CAPITAL INVESTMENT - BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

	Investment, 1982 k$		
	Fly ash	Bottom ash	Total
Direct Investment			
Ash collection	1,193	821	2,014
Ash transportation to disposal site	915	951	1,863
Ash disposal site	8,509	2,127	10,636
Water treatment and recycle	560	141	701
Total process areas	11,177	4,040	15,217
Services, utilities, and miscellaneous	447	162	609
Total direct investment	11,624	4,202	15,826
Indirect Investment			
Engineering design and supervision	343	164	507
Architect and engineering contractor	173	81	254
Construction expense	985	376	1,361
Contractor fees	608	231	839
Total indirect investment	2,109	852	2,961
Contingency	1,373	506	1,879
Total fixed investment	15,106	5,560	20,666
Other Capital Investment			
Allowance for startup and modifications	305	219	524
Interest during construction	2,357	867	3,224
Total depreciable investment	17,768	6,646	24,414
Land	1,560	390	1,950
Working capital	473	185	658
Total capital investment	19,801	7,221	27,022
$/kW	39.60	14.44	54.04

Basis: New, 500-MW, midwestern, dry-bottom, pulverized-coal-fired boiler with a 30-year, 165,000-hour life and a 9,500 Btu/kWh heat rate. Eastern low-calcium coal with a 11,700 Btu/lb heating value, 3.36% sulfur, 15.1% ash, as fired, producing 62,400 lb/hr of ash as 80% fly ash and 20% bottom ash. Fly ash removal to meet 0.03 lb/MBtu NSPS. Separate 30-year fly ash and bottom ash ponds one mile from the power plant based on 55 lb/ft^3 dry bulk density of settled ash, 165,000 hours of operation, and no ash utilization. Costs are projected to mid-1982 and include bottom, economizer, air heater, and ESP ash hoppers and all subsequent equipment and facilities.

TABLE A-4. ANNUAL REVENUE REQUIREMENTS

BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

		Fly ash, 1984 k$		Bottom ash, 1984 k$		Total, 1984 k$
Annual revenue category	Cost, $/unit	Annual quantity	Annual revenue requirements	Annual quantity	Annual revenue requirements	Annual revenue requirements
Direct Costs						
Conversion costs						
Operating labor	15.00/man-hr	7,920 man-hr	118.8	6,930 man-hr	104.0	222.8
Process reagents						
H_2SO_4 (100% equivalent)	65.00/ton	44 tons	2.9	11 tons	0.7	3.6
93% limestone	8.50/ton	46 tons	0.4	11 tons	0.1	0.5
Commercial lime	75.00/ton	36 tons	2.7	9 tons	0.7	3.4
Sodium carbonate	160.00/ton	95 tons	15.1	24 tons	3.8	18.9
Utilities						
Water	0.014/kgal	30,100 kgal	0.4	7,500 kgal	0.1	0.5
Electricity	0.037/kWh	1,684,200 kWh	62.3	654,600 kWh	24.2	86.5
Maintenance						
Process			196.7		135.3	332.0
Pond			176.8		44.2	221.0
Sampling and analysis	21.00/man-hr	1,400 man-hr	29.4	1,400 man-hr	29.4	58.8
Total direct costs			605.5		342.5	948.0
Indirect Costs						
Plant and administrative overheads (60% of conversion costs less utilities)			325.7		190.9	516.6
Total first-year operating and maintenance costs			931.2		533.4	1,464.6
Levelized capital charges (14.7% of total capital investment)			2,910.7		1,061.5	3,972.2
Total first-year annual revenue requirements			3,841.9		1,594.9	5,436.8
Levelized first-year operating and maintenance costs (1.886 x first-year operating and maintenance costs)			1,756.2		1,006.0	2,762.2
Levelized capital charges (14.7% of total capital investment)			2,910.7		1,061.5	3,972.2
Total levelized annual revenue requirements			4,666.9		2,067.5	6,734.4
Equivalent unit revenue requirements						
Unit first-year revenue requirements						
k$			3,842		1,595	5,437
Mills/kWh			1.40		0.58	1.98
$/ton dry ash			27.99		46.47	31.68
Unit levelized revenue requirements						
k$			4,667		2,067	6,734
Mills/kWh			1.70		0.75	2.45
$/ton dry ash			34.00		60.24	39.24

Basis: One-year, 5,500-hour full-load operation of the system described in the capital investment summary; costs projected to mid-1984.

TABLE A-5. CAPITAL INVESTMENT

BASE CASE 3, HOLDING PONDS AND LANDFILL OF NONHARDENING ASH

	Investment, 1982 k$		
	Fly ash	Bottom ash	Total
Direct Investment			
Ash collection	1,195	796	1,991
Ash transportation to disposal site	960	680	1,640
Ash disposal site	4,359	1,064	5,423
Water treatment and recycle	108	31	139
Total process areas	6,622	2,571	9,193
Services, utilities, and miscellaneous	265	103	368
Total direct investment	6,887	2,674	9,561
Indirect Investment			
Engineering design and supervision	251	116	367
Architect and engineering contractor	126	58	184
Construction expense	543	222	765
Contractor fees	330	135	465
Total indirect investment	1,250	531	1,781
Contingency	720	288	1,008
Total fixed investment	8,857	3,493	12,350
Other Capital Investment			
Allowance for startup and modifications	194	147	341
Interest during construction	1,235	496	1,731
Total depreciable investment	10,286	4,136	14,422
Land	848	212	1,060
Working capital	494	153	647
Total capital investment	11,628	4,501	16,129
$/kW	23.26	9.00	32.26

Basis: New, 500-MW, midwestern, dry-bottom, pulverized-coal-fired boiler with a 30-year, 165,000-hour life and a 9,500 Btu/kWh heat rate. Eastern low-calcium coal with a 11,700 Btu/lb heating value, 3.36% sulfur, 15.1% ash, as fired, producing 62,400 lb/hr of ash as 80% fly ash and 20% bottom ash. Fly ash removal to meet 0.03 lb/MBtu NSPS. Separate 5-year ponds for fly ash and bottom ash and combined 25-year landfill 1,600 feet and 1 mile from power plant, respectively, based on 55 lb/ft^3 pond and 90 lb/ft^3 landfill dry bulk density and 165,000 hours of operation and no ash utilization. Costs are projected to mid-1982 and include bottom, economizer, air heater, and ESP ash hoppers and all subsequent equipment and facilities.

TABLE A-6. ANNUAL REVENUE REQUIREMENTS

BASE CASE 3, HOLDING PONDS AND LANDFILL FOR NONHARDENING ASH

		Fly ash, 1984 k$		Bottom ash, 1984 k$		Total, 1984 k$
Annual revenue category	Cost, $/unit	Annual quantity	Annual revenue requirements	Annual quantity	Annual revenue requirements	Annual revenue requirements
Direct Costs						
Conversion costs						
Operating labor	15.00/man-hr	43,560 man-hr	653.4	15,840 man-hr	237.6	891.0
Process reagents						
H_2SO_4 (100% equivalent)	65.00/ton	176 tons	11.4	44 tons	2.9	14.3
Utilities						
Water	0.014/kgal	394,200 kgal	5.5	98,600 kgal	1.4	6.9
Electricity	0.037/kWh	1,020,400 kWh	37.8	237,500 kWh	8.8	46.5
Diesel fuel	1.20/gal	130,000 gal	156.0	32,500 gal	39.0	195.0
Maintenance						
Process			229.9		132.6	362.5
Pond landfill			98.8		24.7	123.5
Sampling and analysis	21.00/man-hr	1,720 man-hr	36.0	1,610 man-hr	33.8	69.9
Contracted ash pumping	1.35/yd^3	135,300 yd^3	182.7			182.7
Total direct costs			1,411.5		480.8	1,892.3
Indirect Costs						
Plant and administrative overheads (60% of conversion costs less utilities)			727.3		259.0	986.3
Total first-year operating and maintenance costs			2,138.8		739.8	2,878.6
Levelized capital charges (14.7% of total capital investment)			1,709.3		661.7	2,371.0
Total first-year annual revenue requirements			3,848.1		1,401.5	5,249.6
Levelized first-year operating and maintenance costs (1.886 x first-year operating and maintenance costs)			4,033.8		1,395.2	5,429.0
Levelized capital charges (14.7% of total capital investment)			1,709.3		661.7	2,371.0
Total levelized annual revenue requirements			5,743.1		2,056.9	7,800.0
Equivalent unit revenue requirements						
Unit first-year revenue requirements						
k$			3,848		1,402	5,250
Mills/kWh			1.40		0.51	1.91
$/ton dry ash			28.03		40.84	30.59
Unit levelized revenue requirements						
k$			5,743		2,057	7,800
Mills/kWh			2.09		0.75	2.84
$/ton dry ash			41.83		59.93	45.45

Basis: One-year, 5,500-hour full-load operation of the system described in the capital investment summary; costs projected to mid-1984.

TABLE A-7. CAPITAL INVESTMENT

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

	Investment, 1982 k$		
	Fly ash	Bottom ash	Total
Direct Investment			
Ash collection	1,400	821	2,221
Ash transportation to disposal site	1,516	1,048	2,564
Ash disposal site	2,280	571	2,851
Water treatment and recycle	54	387	441
Total process areas	5,250	2,827	8,077
Services, utilities, and miscellaneous	210	113	323
Total direct investment	5,460	2,940	8,400
Indirect Investment			
Engineering design and supervision	295	167	462
Architect and engineering contractor	147	84	231
Construction expense	485	282	767
Contractor fees	295	167	462
Total indirect investment	1,222	700	1,922
Contingency	611	350	961
Total fixed investment	7,293	3,990	11,283
Other Capital Investment			
Allowance for startup and modifications	315	252	567
Interest during construction	1,049	601	1,650
Total depreciable investment	8,657	4,843	13,500
Land	568	142	710
Working capital	427	116	543
Total capital investment	9,652	5,101	14,753
$/kW	19.32	10.19	29.51

Basis: New, 500-MW, midwestern, dry-bottom, pulverized-coal-fired boiler with a 30-year, 165,000-hour life and a 9,500 Btu/kWh heat rate. Eastern low-calcium coal with a 11,700 Btu/lb heating value, 3.36% sulfur, 15.1% ash, as fired, producing 62,400 lb/hr of ash as 80% fly ash and 20% bottom ash. Fly ash removal to meet 0.03 lb/MBtu NSPS. Separate fly ash and bottom ash landfills 1 mile from the power plant based on 90 lb/ft^3 dry bulk density of ash, 165,000 hours of operation, and no ash utilization. Costs are projected to mid-1982 and include bottom, economizer, air heater, and ESP ash hoppers and all subsequent equipment and facilities.

TABLE A-8. ANNUAL REVENUE REQUIREMENTS

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

		Fly ash, 1984 k$		Bottom ash, 1984 k$		Total, 1984 k$
Annual revenue category	Cost, $/unit	Annual quantity	Annual revenue requirements	Annual quantity	Annual revenue requirements	Annual revenue requirements
Direct Costs						
Conversion costs						
Operating labor	15.00/man-hr	34,760 man-hr	521.4	18,040 man-hr	270.6	792.0
Process reagents						
H_2SO_4 (100% equivalent)	65.00/ton	132 tons	8.6	198 tons	12.9	21.5
Utilities						
Water	0.014/kgal	3,700 kgal	0.1	900 kgal	0.0	0.1
Electricity	0.037/kWh	543,000 kWh	20.1	199,700 kWh	7.4	27.5
Diesel fuel	1.20/gal	81,600 gal	97.8	20,400 gal	24.5	122.4
Maintenance						
Process			277.9		198.2	476.1
Landfill			60.7		15.2	75.9
Sampling and analysis	21.00/man-hr	820 man-hr	17.2	710 man-hr	14.9	32.0
Total direct costs			1,003.8		543.7	1,547.5
Indirect Costs						
Plant and administrative overheads (60% of conversion costs less utilities)			531.5		307.0	838.5
Total first-year operating and maintenance costs			1,535.3		850.7	2,386.0
Levelized capital charges (14.7% of total capital investment)			1,418.8		749.7	2,168.5
Total first-year annual revenue requirements			2,954.1		1,600.4	4,554.5
Levelized first-year operating and maintenance costs (1.886 x first-year operating and maintenance costs)			2,895.6		1,604.4	4,500.0
Levelized capital charges (14.7% of total capital investment)			1,418.8		749.7	2,168.5
Total levelized annual revenue requirements			4,314.4		2,354.1	6,668.5
Equivalent unit revenue requirements						
Unit first-year revenue requirements						
k$			2,954		1,600	4,554
Mills/kWh			1.08		0.58	1.66
$/ton dry ash			21.52		46.63	26.54
Unit levelized revenue requirements						
k$			4,314		2,354	6,668
Mills/kWh			1.57		0.86	2.42
$/ton dry ash			31.43		68.59	38.86

Basis: One-year, 5,500-hour full-load operation of the system described in the capital investment summary; costs projected to mid-1984.

TABLE A-9. CAPITAL INVESTMENT

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

	Investment, 1982 k$		
	Fly ash	Bottom ash	Total
Direct Investment			
Ash collection	1,163	702	1,865
Ash transportation to disposal site	1,295	921	2,216
Ash disposal site	1,980	495	2,475
Water treatment and recycle	53	356	409
Total process areas	4,491	2,474	6,965
Services, utilities, and miscellaneous	180	99	279
Total direct investment	4,671	2,573	7,244
Indirect Investment			
Engineering design and supervision	243	146	389
Architect and engineering contractor	122	73	195
Construction expense	408	241	649
Contractor fees	243	146	389
Total indirect investment	1,016	606	1,622
Contingency	506	305	811
Total fixed investment	6,193	3,484	9,677
Other Capital Investment			
Allowance for startup and modifications	261	221	482
Interest during construction	869	522	1,391
Total depreciable investment	7,323	4,227	11,550
Land	464	116	580
Working capital	403	112	515
Total capital investment	8,190	4,455	12,645
$/kW	16.38	8.91	25.29

Basis: New, 500-MW, midwestern, dry-bottom, pulverized-coal-fired boiler with a 30-year, 165,000-hour life and a 9,500 Btu/kWh heat rate. Western high-calcium coal with a 9,700 Btu/lb heating value, 0.59% sulfur, 9.7% ash, as fired, producing 47,730 lb/hr of ash as 80% fly ash and 20% bottom ash. Fly ash removal to meet 0.03 lb/MBtu NSPS. Separate fly ash and bottom ash landfills 1 mile from the power plant based on 90 lb/ft^3 dry bulk density of settled ash, 165,000 hours of operation, and no ash utilization. Costs are projected to mid-1982 and include bottom, economizer, air heater, and ESP ash hoppers and all subsequent equipment and facilities.

TABLE A-10. ANNUAL REVENUE REQUIREMENTS

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

		Fly ash, 1984 k$		Bottom ash, 1984 k$		Total, 1984 k$
Annual revenue category	Cost, $/unit	Annual quantity	Annual revenue requirements	Annual quantity	Annual revenue requirements	Annual revenue requirements
Direct Costs						
Conversion costs						
Operating labor	15.00/man-hr	38,280 man-hr	574.2	18,920 man-hr	283.8	858.0
Process reagents						
H_2SO_4 (100% equivalent)	65.00/ton	132 tons	8.6	1,188 tons	77.2	85.8
Utilities						
Water	0.014/kgal	300 kgal	0.1	100 kgal	0.0	0.1
Electricity	0.037/kWh	398,600 kWh	14.7	109,900 kWh	4.1	18.8
Diesel fuel	1.20/gal	73,760 gal	88.5	18,440 gal	22.1	110.6
Maintenance						
Process			242.4		170.1	412.5
Landfill			50.8		12.7	63.5
Sampling and analysis	21.00/man-hr	820 man-hr	17.1	710 man-hr	14.9	32.0
Total direct costs			996.4		584.9	1,581.3
Indirect Costs						
Plant and administrative overheads (60% of conversion costs less utilities)			535.9		335.2	871.1
Total first-year operating and maintenance costs			1,532.3		920.1	2,452.4
Levelized capital charges (14.7% of total capital investment)			1,203.9		654.8	1,858.7
Total first-year annual revenue requirements			2,736.2		1,574.9	4,311.1
Levelized first-year operating and maintenance costs (1.886 x first-year operating and maintenance costs)			2,889.9		1,735.3	4,625.2
Levelized capital charges (14.7% of total capital investment)			1,203.9		654.8	1,858.7
Total levelized annual revenue requirements			4,093.8		2,390.1	6,483.9
Equivalent unit revenue requirements						
Unit first-year revenue requirements						
k$			2,736		1,575	4,311
Mills/kWh			1.00		0.57	1.57
$/ton dry ash			26.06		59.99	32.84
Unit levelized revenue requirements						
k$			4,094		2,390	6,484
Mills/kWh			1.49		0.87	2.36
$/ton dry ash			38.99		91.01	49.40

Basis: One-year, 5,500-hour full-load operation of the system described in the capital investment summary; costs projected to mid-1984.

APPENDIX B

BASE CASE MODULAR CAPITAL INVESTMENT AND ANNUAL REVENUE REQUIREMENTS

TABLE B-1. MODULAR CAPITAL INVESTMENT BY TYPE OF EQUIPMENT

BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Equipment, 1982 k$				Disposal site, 1982 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Investment							
Material cost	773	488	0	0	0	-	1,261
Installation cost	647	717	1,323	0	10,636	-	13,323
Installed cost	1,420	1,205	1,323	0	10,636	-	14,584
Services, utilities, and miscellaneous	57	48	54	0	425	-	584
Total direct investment	1,477	1,253	1,377	0	11,061	-	15,168
Total indirect investment	369	314	343	0	1,770	-	2,796
Contingency	185	156	172	0	1,283	-	1,796
Total fixed investment	2,031	1,723	1,892	0	14,114	-	19,760
Other capital charges	480	405	447	0	2,203	-	3,535
Total depreciable investment	2,511	2,128	2,339	0	16,317	-	23,295
Land	0	0	0	0	1,950	-	1,950
Working capital	80	329	161	0	45	-	615
Total capital investment	2,591	2,457	2,500	0	18,312	-	25,860
$/kW	5.18	4.92	5.00	0	36.62	-	51.72

TABLE B-2. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

Annual revenue category	Equipment, 1984 k$				Disposal site, 1984 k$		Total
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	
Direct Costs							
Conversion costs							
Operating labor	84.2	110.8	3.0	0	8.3	-	206.3
Process reagents							
H_2SO_4 (100% equivalent)	0	0	0	0	3.6	-	3.6
Utilities							
Water	0	6.9	0	0	0	-	6.9
Electricity	0	61.1	0	0	0	-	61.1
Maintenance	118.0	100.0	69.0	0	221.0	-	508.0
Sampling and analysis	0	37.8	0	0	4.2	-	42.0
Total direct costs	202.2	316.6	72.0	0	237.1	-	827.9
Indirect Costs							
Capital charges							
Levelized annual capital charges	380.9	361.2	367.5	0	2,691.8	-	3,801.4
Plant and administrative overheads	121.3	149.2	43.2	0	142.3	-	456.0
Total indirect costs	502.2	510.4	410.7	0	2,834.1	-	4,257.4
Total annual revenue requirements	704.4	827.0	482.7	0	3,071.2	-	5,085.3
Mills/kWh	0.25	0.30	0.18	0	1.12	-	1.85
$/ton dry ash	4.10	4.82	2.81	0	17.90	-	29.63

TABLE B-3. MODULAR CAPITAL INVESTMENT BY TYPE OF EQUIPMENT

BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

	Equipment, 1982 k$				Disposal site, 1982 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Investment							
Material cost	773	667	0	0	0	-	1,440
Installation cost	647	1,171	1,323	0	10,636	-	13,777
Installed cost	1,420	1,838	1,323	0	10,636	-	15,217
Services, utilities, and miscellaneous	57	73	54	0	425	-	609
Total direct investment	1,477	1,911	1,377	0	11,061	-	15,826
Total indirect investment	369	479	343	0	1,770	-	2,961
Contingency	185	239	172	0	1,283	-	1,879
Total fixed investment	2,031	2,629	1,892	0	14,114	-	20,666
Other capital charges	480	618	447	0	2,203	-	3,748
Total depreciable investment	2,511	3,247	2,339	0	16,317	-	24,414
Land	0	0	0	0	1,950	-	1,950
Working capital	80	372	161	0	45	-	658
Total capital investment	2,591	3,619	2,500	0	18,312	-	27,022
$/kW	5.18	7.24	5.00	0	36.62	-	54.04

TABLE B-4. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

Annual revenue category	Equipment, 1984 k$				Disposal site, 1984 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Costs							
Conversion costs							
Operating labor	84.2	127.3	3.0	0	8.3	-	222.8
Process reagents							
H_2SO_4 (100% equivalent)	0	0	0	0	3.6	-	3.6
93% limestone	0	0	0	0	0.5	-	0.5
Commercial lime	0	0	0	0	3.4	-	3.4
Sodium carbonate	0	0	0	0	18.9	-	18.9
Utilities							
Water	0	0.5	0	0	0	-	0.5
Electricity	0	86.5	0	0	0	-	86.5
Maintenance	118.0	145.0	69.0	0	221.0	-	553.0
Sampling and analysis	0	54.6	0	0	4.2	-	58.8
Total direct costs	202.2	413.9	72.0	0	259.9	-	948.0
Indirect Costs							
Capital charges							
Levelized annual capital charges	380.9	532.0	367.5	0	2,691.8	-	3,972.2
Plant and administrative overheads	121.3	196.1	43.2	0	155.9	-	516.6
Total indirect costs	502.2	728.1	410.7	0	2,847.7	-	4,488.8
Total annual revenue requirements	704.4	1,142.0	482.7	0	3,107.6	-	5,436.8
Mills/kWh	0.25	0.42	0.18	0	1.13	-	1.98
$/ton dry ash	4.10	6.66	2.81	0	18.11	-	31.68

TABLE B-5. MODULAR CAPITAL INVESTMENT BY TYPE OF EQUIPMENT

BASE CASE 3, HOLDING PONDS AND LANDFILL OF NONHARDENING ASH

	Equipment, 1982 k$				Disposal site, 1982 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Investment							
Material cost	773	480	0	1,208	0	0	2,461
Installation cost	647	728	352	0	3,142	1,863	6,732
Installed cost	1,420	1,208	352	1,208	3,142	1,863	9,193
Services, utilities, and miscellaneous	57	48	14	48	126	75	368
Total direct investment	1,477	1,256	366	1,256	3,268	1,938	9,561
Total indirect investment	369	314	92	0	522	484	1,781
Contingency	185	156	46	0	379	242	1,008
Total fixed investment	2,031	1,726	504	1,256	4,169	2,664	12,350
Other capital charges	480	408	118	0	650	416	2,072
Total depreciable investment	2,511	2,134	622	1,256	4,819	3,080	14,422
Land	0	0	0	0	510	550	1,060
Working capital	80	215	76	126	53	97	647
Total capital investment	2,591	2,349	698	1,382	5,382	3,727	16,129
$/kW	5.18	4.70	1.40	2.76	10.76	7.45	32.26

TABLE B-6. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 3, HOLDING PONDS AND LANDFILL FOR NONHARDENING ASH

	Equipment, 1984 k$				Disposal site, 1984 k$		
Annual revenue category	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Costs							
Conversion costs							
Operating labor	84.2	110.8	3.0	625.0	2.0	66.0	891.0
Process reagents							
H_2SO_4 (100% equivalent)	0	0	0	0	3.6	10.7	14.3
Utilities							
Water	0	6.9	0	0	0	0	6.9
Electricity	0	46.5	0	0	0	0	46.5
Diesel fuel	0	0	0	195.0	0	0	195.0
Maintenance	118.0	100.6	18.3	125.6	65.4	58.1	486.0
Sampling and analysis	0	65.7	0	0	2.1	2.1	69.9
Contracted ash pumping	0	0	0	0	182.7	0	182.7
Total direct costs	202.2	330.5	21.3	945.6	255.8	136.9	1,892.3
Indirect Costs							
Capital charges							
Levelized annual capital charges	380.9	345.3	102.6	203.2	791.2	547.8	2,371.0
Plant and administrative overheads	121.3	166.2	12.8	450.4	153.5	82.1	986.3
Total indirect costs	502.2	511.5	115.4	653.6	944.7	629.9	3,357.3
Total annual revenue requirements	704.4	842.0	136.7	1,599.2	1,200.5	766.8	5,249.6
Mills/kWh	0.25	0.31	0.05	0.58	0.44	0.28	1.91
$/ton dry ash	4.10	4.91	0.80	9.32	7.00	4.47	30.59

TABLE B-7. MODULAR CAPITAL INVESTMENT BY TYPE OF EQUIPMENT

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

	Equipment, 1982 k$				Disposal site, 1982 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Investment							
Material cost	773	1,828	0	682	-	0	3,283
Installation cost	647	1,639	75	0	-	2,433	4,794
Installed cost	1,420	3,467	75	682	-	2,433	8,077
Services, utilities, and miscellaneous	57	139	3	27	-	97	323
Total direct investment	1,477	3,606	78	709	-	2,530	8,400
Total indirect investment	369	901	20	0	-	632	1,922
Contingency	185	450	10	0	-	316	961
Total fixed investment	2,031	4,957	108	709	-	3,478	11,283
Other capital charges	480	1,169	25	0	-	543	2,217
Total depreciable investment	2,511	6,126	133	709	-	4,021	13,500
Land	0	0	0	0	-	710	710
Working capital	80	259	8	71	-	125	543
Total capital investment	2,591	6,385	141	780	-	4,856	14,753
$/kW	5.18	12.77	0.28	1.56	-	9.71	29.51

TABLE B-8. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

	Equipment, 1984 k$				Disposal site, 1984 k$		
Annual revenue category	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Costs							
Conversion costs							
Operating labor	84.2	110.8	1.5	529.5	-	66.0	792.0
Process reagents							
H_2SO_4 (100% equivalent)	0	10.7	0	0	-	10.8	21.5
Utilities							
Water	0	0.1	0	0	-	0	0.1
Electricity	0	27.5	0	0	-	0	27.5
Diesel fuel	0	0	0	122.4	-	0	122.4
Maintenance	118.0	283.3	3.9	70.9	-	75.9	552.0
Sampling and analysis	0	27.8	0	0	-	4.2	32.0
Total direct costs	202.2	460.2	5.4	722.8	-	156.9	1,547.5
Indirect Costs							
Capital charges							
Levelized annual capital charges	360.8	937.0	22.3	114.7	-	713.7	2,168.5
Plant and administrative overheads	121.3	259.6	3.2	360.2	-	94.1	838.5
Total indirect costs	502.2	1,196.6	25.5	474.9	-	807.8	3,007.0
Total annual revenue requirements	704.4	1,656.8	30.9	1,197.7	-	964.7	4,554.5
Mills/kWh	0.25	0.60	0.01	0.44	-	0.35	1.66
$/ton dry ash	4.10	9.65	0.18	6.98	-	5.62	26.54

TABLE B-9. MODULAR CAPITAL INVESTMENT BY TYPE OF EQUIPMENT

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

	Equipment, 1982 k$				Disposal site, 1982 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Investment							
Material cost	666	1,538	0	734	-	0	2,938
Installation cost	557	1,358	75	0	-	2,037	4,027
Installed cost	1,223	2,896	75	734	-	2,037	6,965
Services, utilities, and miscellaneous	49	116	3	29	-	81	279
Total direct investment	1,272	3,012	78	763	-	2,118	7,244
Total indirect investment	318	753	20	0	-	530	1,622
Contingency	159	376	10	0	-	266	811
Total fixed investment	1,749	4,141	108	763	-	2,914	9,677
Other capital charges	413	980	25	0	-	455	1,873
Total depreciable investment	2,162	5,121	133	763	-	3,369	11,550
Land	0	0	0	0	-	580	580
Working capital	69	255	10	76	-	105	515
Total capital investment	2,231	5,376	143	839	-	4,054	12,645
$/kW	4.46	10.75	0.29	1.68	-	8.11	25.29

TABLE B-10. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

Annual revenue category	Equipment, 1984 k$				Disposal site, 1984 k$		
	Hoppers	Process	Pipelines	Mobile equipment	Pond	Landfill	Total
Direct Costs							
Conversion costs							
Operating labor	84.2	110.8	1.5	595.5	-	66.0	858.0
Process reagents							
H_2SO_4 (100% equivalent)	0	75.1	0	0	-	10.7	85.8
Utilities							
Water	0	0.1	0	0	-	0	0.1
Electricity	0	18.8	0	0	-	0	18.8
Diesel fuel	0	0	0	110.6	-	0	110.6
Maintenance	101.8	230.5	3.9	76.3	-	63.5	476.0
Sampling and analysis	0	27.8	0	0	-	4.2	32.0
Total direct costs	186.0	463.1	5.4	782.4	-	144.4	1,581.3
Indirect Costs							
Capital charges							
Levelized annual capital charges	328.0	789.2	22.3	123.3	-	595.9	1,858.7
Plant and administrative overheads	111.6	266.5	3.2	403.1	-	86.6	871.1
Total indirect costs	439.6	1,055.7	25.5	526.4	-	682.5	2,729.8
Total annual revenue requirements	625.6	1,518.8	30.9	1,308.8	-	826.9	4,311.1
Mills/kWh	0.23	0.55	0.01	0.48	-	0 30	1.57
$/ton dry ash	4.77	11.57	0.23	9.97	-	6.30	32.84

TABLE B-11. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Fly ash process areas, 1982 k$					Bottom ash process areas, 1982 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total direct capital investment
Direct Investment											
Material cost	706	44	-	12	762	386	110	-	3	499	1,261
Installation cost	487	871	8,509	42	9,909	435	841	2,127	11	3,414	13,323
Installed cost	1,193	915	8,509	54	10,671	821	951	2,127	14	3,913	14,584
Services, utilities, miscellaneous	48	37	340	2	427	33	38	85	1	157	584
Total direct investment	1,241	952	8,849	56	11,098	854	989	2,212	15	4,070	15,168
Indirect Investment											
Engineering design and supervision	75	58	176	3	312	51	59	44	1	155	467
Architect and engineering	37	28	90	2	157	25	30	22	0	77	234
Construction expense	124	95	708	6	933	85	99	177	2	363	1,296
Contractor fees	75	58	441	3	577	51	59	111	1	222	799
Total indirect investment	311	239	1,415	14	1,979	212	247	354	4	817	2,796
Contingency	155	119	1,026	7	1,307	107	123	257	2	489	1,796
Total fixed investment	1,707	1,310	11,290	77	14,384	1,173	1,359	2,823	21	5,376	19,760
Other Capital Charges											
Allowance for startup and modifications	137	105	0	6	248	94	108	0	2	204	452
Interest during construction	268	203	1,762	12	2,245	183	212	440	3	838	3,083
Total depreciable investment	2,112	1,618	13,052	95	16,877	1,450	1,679	3,263	26	6,418	23,295
Land	0	0	1,560	0	1,560	0	0	390	0	390	1,950
Working capital	225	173	36	10	444	74	86	9	2	171	615
Total capital investment	2,337	1,791	14,648	105	18,881	1,524	1,765	3,662	28	6,979	25,860
$/kW	4.67	3.58	29.30	0.21	37.76	3.05	3.53	7.32	0.06	13.96	51.72

TABLE B-12. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

BASE CASE 1, DIRECT PONDING OF NONHARDENING ASH WITHOUT WATER REUSE

	Fly ash process areas, 1984 k$					Bottom ash process areas, 1984 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total annual revenue requirements
Direct Costs											
Conversion costs											
Operating labor	90.0	9.0	6.4	0.2	105.6	49.5	49.5	1.5	0.1	100.7	206.3
Process reagents											
H_2SO_4 (100% equivalent)	0	0	0	2.9	2.9	0	0	0	0.7	0.7	3.6
Utilities											
Water	0	5.5	0	0	5.5	0	1.4	0	0	1.4	6.9
Electricity	30.5	10.3	0.5	0.7	42.0	7.8	10.9	0.2	0.2	19.1	61.1
Maintenance											
Process	100.0	57.0	-	4.0	161.0	68.0	57.0	-	1.0	126.0	287.0
Ponds	-	-	177.0	-	177.0	-	-	44.0	-	44.0	221.0
Sampling and analysis	2.1	0	2.1	16.8	21.0	2.1	0	2.1	16.8	21.0	42.0
Total direct costs	222.6	81.8	186.0	24.6	515.0	127.4	118.9	47.8	18.8	312.9	827.9
Indirect Costs											
Levelized annual capital charge	343.5	263.3	2,153.3	15.4	2,775.5	224.0	259.5	538.3	4.1	1,025.9	3,801.4
Plant and administrative overheads	115.3	39.6	111.3	14.3	280.5	71.7	64.0	28.6	11.2	175.5	456.0
Total indirect costs	458.8	302.9	2,264.6	29.7	3,056.0	295.7	323.5	566.9	15.3	1,201.4	4,257.4
Total annual revenue requirements	681.4	384.7	2,450.6	54.3	3,571.0	423.1	442.4	614.7	34.1	1,514.3	5,085.3
Mills/kWh	0.25	0.14	0.89	0.02	1.30	0.15	0.17	0.22	0.01	0.55	1.85
$/ton dry ash	4.96	2.80	17.85	0.40	26.01	12.32	12.89	17.92	0.99	44.12	29.63

TABLE B-13. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

	Fly ash process areas, 1982 k$					Bottom ash process areas, 1982 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total direct capital investment
Direct Investment											
Material cost	706	44	-	154	904	386	110	-	40	536	1,440
Installation cost	487	871	8,509	406	10,273	435	841	2,127	101	3,504	13,777
Installed cost	1,193	915	8,509	560	11,177	821	951	2,127	141	4,040	15,217
Services, utilities, miscellaneous	48	37	340	22	447	33	38	85	6	162	609
Total direct investment	1,241	952	8,849	582	11,624	854	989	2,212	147	4,202	15,826
Indirect Investment											
Engineering design and supervision	75	58	176	34	343	51	59	44	10	164	507
Architect and engineering	37	28	90	18	173	25	30	22	4	81	254
Construction expense	124	95	708	58	985	85	99	177	15	376	1,361
Contractor fees	75	58	441	34	608	51	59	111	10	231	839
Total indirect investment	311	239	1,415	144	2,109	212	247	354	39	852	2,961
Contingency	155	119	1,026	73	1,373	107	123	257	19	506	1,879
Total fixed investment	1,707	1,310	11,290	799	15,106	1,173	1,359	2,823	205	5,560	20,666
Other Capital Charges											
Allowance for startup and modifications	137	105	0	63	305	94	108	0	17	219	524
Interest during construction	268	203	1,762	124	2,357	183	212	440	32	867	3,224
Total depreciable investment	2,112	1,618	13,052	986	17,768	1,450	1,679	3,263	254	6,646	24,414
Land	0	0	1,560	0	1,560	0	0	390	0	390	1,950
Working capital	225	173	36	39	473	74	86	9	16	185	658
Total capital investment	2,337	1,791	14,648	1,025	19,801	1,524	1,765	3,662	270	7,221	27,022
$/kW	4.67	3.58	29.30	2.05	39.60	3.05	3.53	7.32	0.54	14.44	54.04

TABLE B-14. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

BASE CASE 2, DIRECT PONDING OF NONHARDENING ASH WITH WATER REUSE

	Fly ash process areas, 1984 k$					Bottom ash process areas, 1984 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total annual revenue requirements
Direct Costs											
Conversion costs											
Operating labor	90.0	9.0	6.4	13.4	118.8	49.5	49.5	1.6	3.4	104.0	222.8
Process reagents											
H_2SO_4 (100% equivalent)	0	0	0	2.9	2.9	0	0	0	0.7	0.7	3.6
93% limestone	-	-	-	0.4	0.4	-	-	-	0.1	0.1	0.5
Commercial lime	-	-	-	2.7	2.7	-	-	-	0.7	0.7	3.4
Sodium carbonate	-	-	-	15.1	15.1	-	-	-	3.8	3.8	18.9
Utilities											
Water	0	0.4	0	0	0.4	0	0.1	0	0	0.1	0.5
Electricity	30.5	10.3	0.5	21.0	62.3	7.8	10.9	0.2	5.3	24.2	86.5
Maintenance											
Process	100.0	57.0	-	39.5	196.5	68.0	57.0	-	10.5	135.5	332.0
Ponds	-	-	177.0	-	177.0	-	-	44.0	-	44.0	221.0
Sampling and analysis	2.1	0	2.1	25.2	29.4	2.1	0	2.1	25.2	29.4	58.8
Total direct costs	222.6	76.7	186.0	120.2	605.5	127.4	117.5	47.9	49.7	342.5	948.0
Indirect Costs											
Levelized annual capital charge	343.5	263.3	2,153.3	150.6	2,910.7	224.0	259.5	538.3	39.7	1,061.5	3,972.2
Plant and administrative overheads	115.3	39.6	111.3	59.5	325.7	71.7	63.9	28.6	26.7	190.9	516.6
Total indirect costs	458.8	302.9	2,264.6	210.1	3,236.4	295.7	323.4	566.9	66.4	1,252.4	4,488.8
Total annual revenue requirements	681.4	379.6	2,450.6	330.3	3,841.9	423.1	440.4	614.8	116.1	1,594.9	5,436.8
Mills/kWh	0.25	0.14	0.89	0.12	1.40	0.15	0.17	0.22	0.04	0.58	1.98
$/ton dry ash	4.96	2.77	17.85	2.41	27.99	12.32	12.85	17.92	3.38	46.47	31.68

TABLE B-15. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

BASE CASE 3, HOLDING PONDS AND LANDFILL OF NONHARDENING ASH

	Fly ash process areas, 1982 k$					Bottom ash process areas, 1982 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total direct capital investment
Direct Investment											
Material cost	706	604	334	24	1,668	370	333	84	6	793	2,461
Installation cost	489	356	4,025	84	4,954	426	347	980	25	1,778	6,732
Installed cost	1,195	960	4,359	108	6,622	796	680	1,064	31	2,571	9,193
Services, utilities, miscellaneous	48	38	174	5	265	32	27	43	1	103	368
Total direct investment	1,243	998	4,533	113	6,887	828	707	1,107	32	2,674	9,561
Indirect Investment											
Engineering design and supervision	75	25	144	7	251	50	28	36	2	116	367
Architect and engineering	37	12	74	3	126	25	14	18	1	58	184
Construction expense	124	41	367	11	543	83	47	89	3	222	765
Contractor fees	75	25	223	7	330	50	28	55	2	135	465
Total indirect investment	311	103	808	28	1,250	208	117	198	8	531	1,781
Contingency	155	51	500	14	720	104	59	121	4	288	1,008
Total fixed investment	1,709	1,152	5,841	155	8,857	1,140	883	1,426	44	3,493	12,350
Other Capital Charges											
Allowance for startup and modifications	137	45	0	12	194	91	53	0	3	147	341
Interest during construction	269	88	854	24	1,235	178	101	210	7	496	1,731
Total depreciable investment	2,115	1,285	6,695	191	10,286	1,409	1,037	1,636	54	4,136	14,422
Land	0	0	848	0	848	0	0	212	0	212	1,060
Working capital	225	167	77	25	494	72	58	20	3	153	647
Total capital investment	2,340	1,452	7,620	216	11,628	1,481	1,095	1,868	57	4,501	16,129
$/kW	4.67	2.90	15.26	0.43	23.26	2.96	2.19	3.74	0.11	9.00	32.26

TABLE B-16. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

BASE CASE 3, HOLDING PONDS AND LANDFILL OF NONHARDENING ASH

	Fly ash process areas, 1984 k$					Bottom ash process areas, 1984 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total annual revenue requirements
Direct Costs											
Conversion costs											
Operating labor	90.0	299.0	264.0	0.4	653.4	49.5	121.9	66.0	0.2	237.6	891.0
Process reagents											
H_2SO_4 (100% equivalent)	0	0	0	11.4	11.4	0	0	0	2.9	2.9	14.3
Utilities											
Water	0	5.5	0	0	5.5	0	1.4	0	0	1.4	6.9
Electricity	28.7	7.3	1.1	0.7	37.8	3.3	5.0	0.3	0.2	8.8	46.5
Diesel fuel	0	84.3	71.7	0	156.0	0	24.7	14.3	0	39.0	195.0
Maintenance											
Process	100.0	86.0	35.8	8.0	229.8	66.0	54.0	10.2	3.0	133.2	363.0
Ponds + landfill	-	-	98.9	-	98.9	-	-	24.1	-	24.1	123.0
Sampling and analysis	2.1	0	4.2	29.7	36.0	2.1	0	4.2	27.5	33.8	69.9
Contracted ash pumping	-	182.7	-	-	182.7	-	-	-	-	-	182.7
Total direct costs	220.8	664.8	475.7	50.2	1,411.5	120.9	207.0	119.1	33.8	480.8	1,892.3
Indirect Costs											
Levelized annual capital charge	344.0	213.4	1,120.1	31.8	1,709.3	217.7	161.0	274.6	8.4	661.7	2,371.0
Plant and administrative overheads	115.3	340.6	241.7	29.7	727.3	70.6	105.5	62.7	20.2	259.0	986.3
Total indirect costs	459.3	554.0	1,361.8	61.5	2,436.6	288.3	266.5	33..3	28.6	920.7	3,357.3
Total annual revenue requirements	680.1	1,218.8	1,837.5	111.7	3,848.1	409.2	473.5	456.4	62.4	1,401.5	5,249.6
Mills/kWh	0.25	0.44	0.67	0.04	1.40	0.15	0.17	0.17	0.02	0.51	1.91
$/ton dry ash	4.95	8.88	13.39	0.81	28.03	11.92	13.79	13.31	1.82	40.84	30.59

TABLE B-17. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

	Fly ash process areas, 1982 k$					Bottom ash process areas, 1982 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total direct capital investment
Direct Investment											
Material cost	834	940	334	12	2,120	386	558	84	135	1,163	3,283
Installation cost	566	576	1,946	42	3,130	435	490	487	252	1,664	4,794
Installed cost	1,400	1,516	2,280	54	5,250	821	1,048	571	387	2,827	8,077
Services, utilities, miscellaneous	56	61	91	2	210	33	42	23	15	113	323
Total direct investment	1,456	1,577	2,371	56	5,460	854	1,090	594	402	2,940	8,400
Indirect Investment											
Engineering design and supervision	87	81	124	3	295	51	62	30	24	167	462
Architect and engineering	44	40	61	2	147	25	31	16	12	84	231
Construction expense	146	136	197	6	485	85	104	53	40	282	767
Contractor fees	87	81	124	3	295	51	62	30	24	167	462
Total indirect investment	364	338	506	14	1,222	212	259	129	100	700	1,922
Contingency	182	170	252	7	611	107	129	64	50	350	961
Total fixed investment	2,002	2,085	3,129	77	7,293	1,173	1,478	787	552	3,990	11,283
Other Capital Charges											
Allowance for startup and modifications	160	149	0	6	315	94	114	0	44	252	567
Interest during construction	312	291	434	12	1,049	183	222	110	86	601	1,650
Total depreciable investment	2,474	2,525	3,563	95	8,657	1,450	1,814	897	682	4,843	13,500
Land	0	0	568	0	568	0	0	142	0	142	710
Working capital	260	57	100	10	427	74	10	25	7	116	543
Total capital investment	2,734	2,582	4,231	105	9,652	1,524	1,824	1,064	689	5,101	14,753
$/kW	5.47	5.16	8.46	0.21	19.32	3.05	3.65	2.11	1.38	10.19	29.51

TABLE B-18. MODULAR ANNUAL REVENUE REQUIREMENTS BY PROCESS AREA

BASE CASE 4, DIRECT LANDFILL OF NONHARDENING ASH

	Fly ash process areas, 1984 k$					Bottom ash process areas, 1984 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total annual revenue requirements
Direct Costs											
Conversion costs											
Operating labor	90.0	114.4	316.8	0.2	521.4	49.5	75.9	79.2	66.0	270.6	792.0
Process reagents											
H_2SO_4 (100% equivalent)	0	0	0	8.6	8.6	0	0	0	12.9	12.9	21.5
Utilities											
Water	0	0.1	0	0	0.1	0	0	0	0	0.0	0.1
Electricity	16.1	2.5	0.8	0.7	20.1	4.4	2.4	0.2	0.4	7.4	27.5
Diesel fuel	0	26.1	71.7	0	97.8	0	10.2	14.3	0	24.5	122.4
Maintenance											
Process	116.0	129.0	28.9	4.0	277.9	68.0	83.0	15.2	32.0	198.2	476.1
Landfills	-	-	60.7	-	60.7	-	-	15.2	-	15.2	75.9
Sampling and analysis	2.1	0	2.1	13.0	17.2	2.1	0	2.1	10.7	14.9	32.0
Total direct costs	224.2	272.1	481.0	26.5	1,003.8	124.0	171.5	126.2	122.0	543.7	1,547.5
Indirect Costs											
Levelized annual capital charge	401.8	379.6	622.0	15.4	1,418.8	224.0	268.0	156.4	101.3	749.7	2,168.5
Plant and administrative overheads	124.9	146.0	245.1	15.5	531.5	71.7	95.3	67.0	73.0	307.0	838.5
Total indirect costs	526.7	525.6	867.1	30.9	1,950.3	295.7	363.3	223.4	174.3	1,056.7	3,007.0
Total annual revenue requirements	750.9	797.7	1,348.1	57.4	2,954.1	419.7	534.8	349.6	296.3	1,600.4	4,554.5
Mills/kWh	0.27	0.29	0.50	0.02	1.08	0.15	0.19	0.13	0.11	0.58	1.66
$/ton dry ash	5.46	5.81	9.83	0.42	21.52	12.23	15.58	10.19	8.63	46.63	26.54

TABLE B-19. MODULAR CAPITAL INVESTMENT BY PROCESS AREA

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

	Fly ash process areas, 1982 k$					Bottom ash process areas, 1982 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total direct capital investment
Direct Investment											
Material cost	693	833	350	12	1,888	339	493	88	130	1,050	2,938
Installation cost	470	462	1,630	41	2,603	363	428	407	226	1,424	4,027
Installed cost	1,163	1,295	1,980	53	4,491	702	921	495	356	2,474	6,965
Services, utilities, miscellaneous	46	53	79	2	180	28	37	20	14	99	279
Total direct investment	1,209	1,348	2,059	55	4,671	730	958	515	370	2,573	7,244
Indirect Investment											
Engineering design and supervision	73	65	102	3	243	44	54	26	22	146	389
Architect and engineering	36	33	51	2	122	22	27	13	11	73	195
Construction expense	121	109	171	7	408	73	91	40	37	241	649
Contractor fees	73	65	102	3	243	44	54	26	22	146	389
Total indirect investment	303	272	426	15	1,016	183	226	105	92	606	1,622
Contingency	151	136	212	7	506	91	113	55	46	305	811
Total fixed investment	1,663	1,756	2,697	77	6,193	1,004	1,297	675	508	3,484	9,677
Other Capital Charges											
Allowance for startup and modifications	133	122	0	6	261	80	100	0	41	221	482
Interest during construction	259	234	364	12	869	157	195	91	79	522	1,391
Total depreciable investment	2,055	2,112	3,061	95	7,323	1,241	1,592	766	628	4,227	11,550
Land	0	0	464	0	464	0	0	116	0	116	580
Working capital	217	92	84	10	403	63	18	21	10	112	515
Total capital investment	2,272	2,204	3,609	105	8,190	1,304	1,610	903	638	4,455	12,645
$/kW	4.54	4.40	7.23	0.21	16.38	2.61	3.22	1.80	1.28	8.91	25.29

TABLE B-20. MODULAR ANNUAL REVENUE REQUIREMENTS BY TYPE OF EQUIPMENT

BASE CASE 5, DIRECT LANDFILL OF SELF-HARDENING ASH

	Fly ash process areas, 1984 k$					Bottom ash process areas, 1984 k$					
	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Collection	Transportation to disposal site	Disposal site	Water treatment and recycle	Subtotal	Total annual revenue requirements
Direct Costs											
Conversion costs											
Operating labor	90.0	140.8	343.4	0.2	574.2	49.5	82.5	85.8	66.0	283.8	858.0
Process reagents											
H_2SO_4 (100% equivalent)	0	0	0	8.6	8.6	0	0	0	77.2	77.2	85.8
Utilities											
Water	0	0.1	0	0	0.1	0	0	0	0	0	0.1
Electricity	10.8	2.5	0.7	0.7	14.7	2.5	1.2	0.1	0.3	4.1	18.8
Diesel fuel	0	23.6	64.9	0	88.5	0	9.2	12.9	0	22.1	110.6
Maintenance											
Process	97.0	107.0	34.2	4.0	242.4	58.0	72.0	11.1	29.0	170.1	412.5
Landfills	-	-	50.8	-	50.8	-	-	12.7	-	12.7	63.5
Sampling and analysis	2.1	0	2.0	13.0	17.1	2.1	0	2.1	10.7	14.9	32.0
Total direct costs	199.9	274.0	496.0	26.5	996.4	112.1	164.9	124.7	183.2	584.9	1,581.3
Indirect Costs											
Levelized annual capital charge	334.0	324.0	530.5	15.4	1,203.9	191.7	236.7	132.6	93.8	654.8	1,858.7
Plant and administrative overheads	113.5	148.7	258.2	15.5	535.9	65.8	92.7	67.0	109.7	335.2	871.1
Total indirect costs	447.5	472.7	788.7	30.9	1,739.8	257.5	329.4	199.6	203.5	990.0	2,729.8
Total annual revenue requirements	647.4	746.7	1,284.7	57.4	2,736.2	369.6	494.3	324.3	386.7	1,574.9	4,311.1
Mills/kWh	0.24	0.26	0.47	0.02	0.99	0.13	0.17	0.12	0.14	0.56	1.57
$/ton dry ash	6.17	7.11	12.23	0.55	26.06	14.07	18.83	12.35	14.72	59.97	32.84